

The Higgs Boson at the LHC and Beyond

Sven Heinemeyer, IFCA (Santander)

Jaca, 05/2007

- 1.** The Higgs Boson in the SM
- 2.** The Higgs Boson in the MSSM

The Higgs Boson in the SM and Beyond

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The Higgs Boson in/at the SM/LHC and Beyond (I)

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2. The Higgs Boson in the MSSM

The Higgs Boson in/at the SM/LHC and Beyond (I)

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1. Higgs Theory
2. Electroweak Precision Observables
3. Properties of the SM Higgs boson
4. SM Higgs boson Searches at LEP
5. SM Higgs boson Searches at the Tevatron
6. SM Higgs boson Searches at the LHC
7. SM Higgs boson precision physics at the ILC

1. Higgs Theory

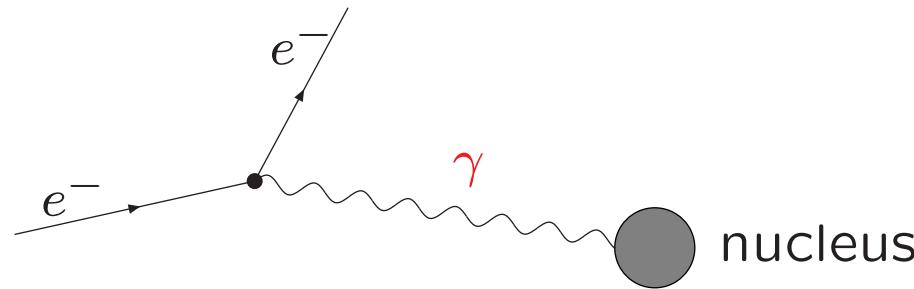
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory \Rightarrow interaction: exchange of field quanta

Construction principle of the SM: **gauge invariance**

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ



\mathcal{L}_{QED} invariant under **gauge transformation**:

$$\Psi \rightarrow e^{ie\lambda(x)}\Psi, A_\mu \rightarrow A_\mu + \partial_\mu\lambda(x)$$

mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant

$\Rightarrow A_\mu$ is massless gauge field

Problem:

Gauge fields Z, W^+, W^- are **massive**

explicite mass terms in the Lagrangian \Leftrightarrow breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

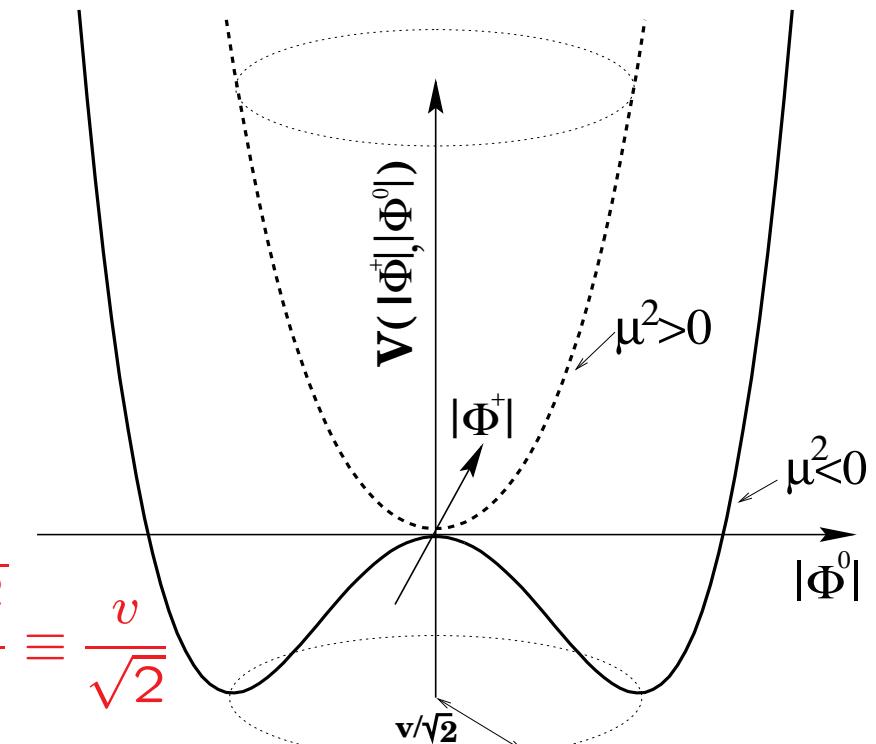
$$\text{Scalar SU(2) doublet: } \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Higgs potential:

$$V(\phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (\text{unitary gauge})$$

H : elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{d}_L \Phi d_R - g_u \bar{u}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

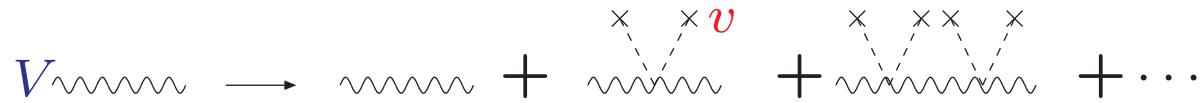
with

$$\begin{aligned} iD_\mu &= i\partial - g_2 \vec{I} \vec{W} - g_1 Y B \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad \qquad \qquad \Phi \rightarrow \begin{pmatrix} 0 \\ v \end{pmatrix}, \Phi_c \rightarrow \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

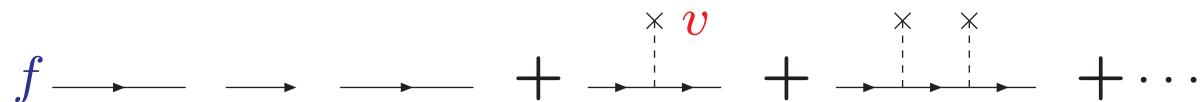
⇒ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



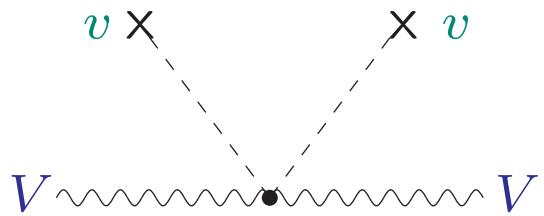
$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} + \sum_j \frac{1}{q^2} \left[\left(\frac{gv}{\sqrt{2}} \right)^2 \frac{1}{q^2} \right]^j = \frac{1}{q^2 - M^2} : M^2 = g^2 \frac{v^2}{2}$$

2.) fermion mass terms: Yukawa couplings:

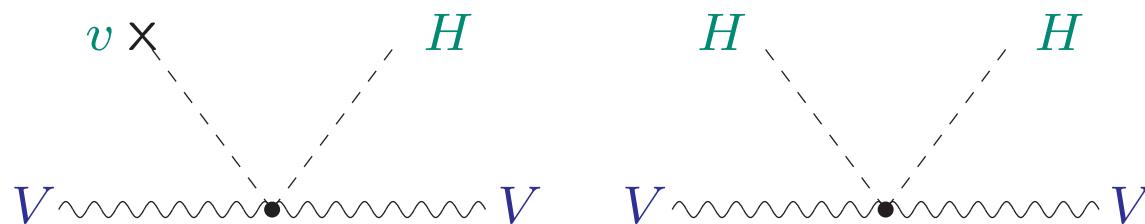


$$\frac{1}{q} \rightarrow \frac{1}{q} + \sum_j \frac{1}{q} \left[\frac{g_f v}{\sqrt{2}} \frac{1}{q} \right]^j = \frac{1}{q - m_f} : m_f = g_f \frac{v}{\sqrt{2}}$$

1.) $VV\Phi\Phi$ coupling:



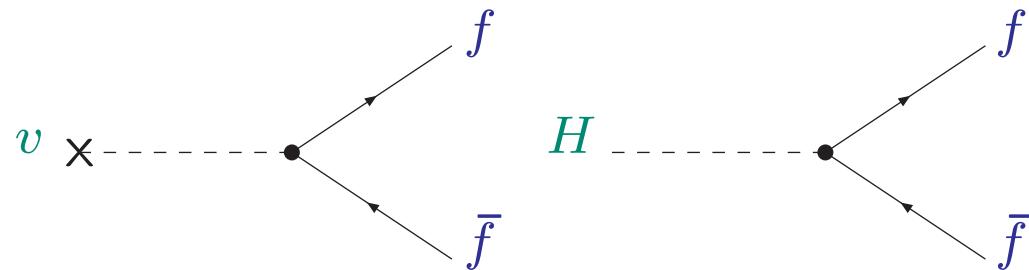
⇒ VV mass terms: $g_2^2 v^2 / 2 \equiv M_W^2, (g_1^2 + g_2^2) v^2 / 2 \equiv M_Z^2$



⇒ triple/quartic couplings to gauge bosons

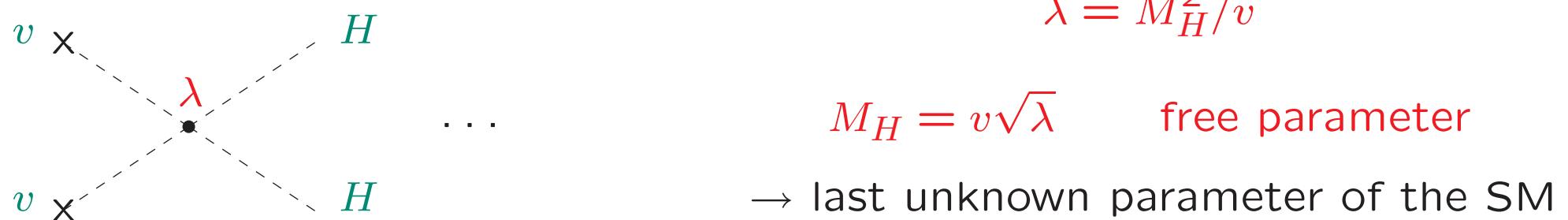
⇒ coupling \propto masses

2.) fermion mass terms: Yukawa couplings



$$m_f = v g_f \Rightarrow \text{coupling} \propto \text{masses}$$

3.) mass of the Higgs boson: self coupling



⇒ establish Higgs mechanism ≡ find the Higgs ⊕ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \rightarrow W_L W_L$

$$\mathcal{M}_V = \text{Diagram showing two incoming } W_L \text{ bosons scattering into two outgoing } W_L \text{ bosons via } \gamma, Z \text{ exchange} + \text{Diagram showing two incoming } W_L \text{ bosons scattering into two outgoing } W_L \text{ bosons via } \gamma, Z \text{ exchange} + \text{Diagram showing two incoming } W_L \text{ bosons scattering into two outgoing } W_L \text{ bosons via } \gamma, Z \text{ exchange} = -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1) \text{ for } E \rightarrow \infty$$

⇒ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$$\mathcal{M}_S = \text{Diagram showing two incoming } W_L \text{ bosons scattering into two outgoing } W_L \text{ bosons via } H \text{ exchange} + \text{Diagram showing two incoming } W_L \text{ bosons scattering into two outgoing } W_L \text{ bosons via } H \text{ exchange} = g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1) \text{ for } E \rightarrow \infty$$

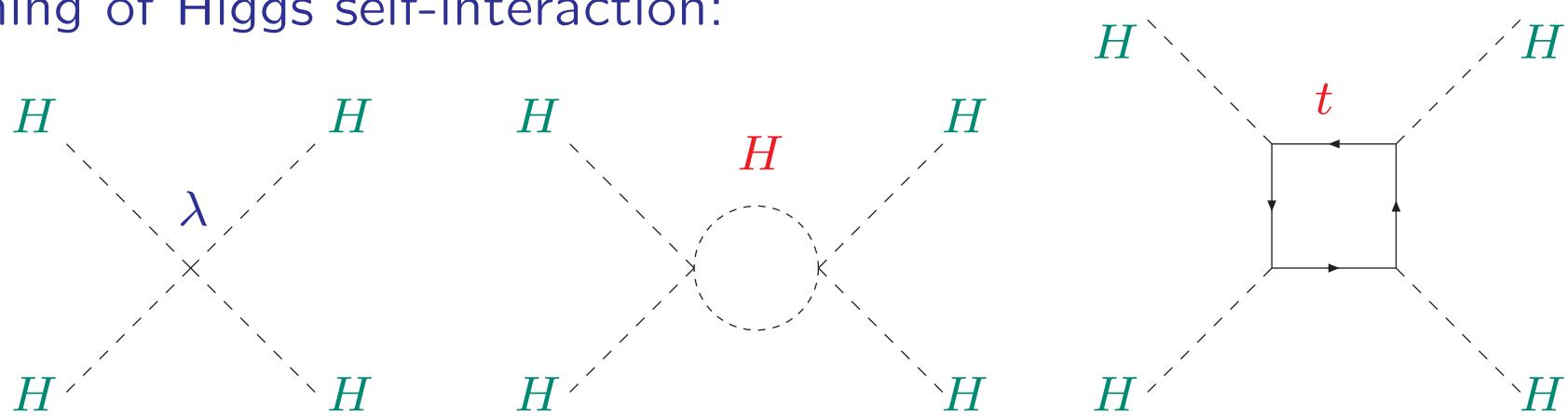
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} (g_{WWH}^2 - g^2 M_W^2) + \dots$$

⇒ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g M_W$$

What else do we know about the Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2} \left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16} (2g_2^4 + (g_2^2 + g_1^2)^2) \right], \quad t = \log \left(\frac{Q^2}{v^2} \right)$$

Two conditions:

- 1.) avoid Landau pole (for large $\lambda \sim M_H^2$)
- 2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2} [\lambda^2]$$

$$\Rightarrow \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2} \log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \Rightarrow M_H^2 \leq \frac{8\pi^2 v^2}{3 \log\left(\frac{\Lambda^2}{v^2}\right)} \quad : \text{upper bound on } M_H$$

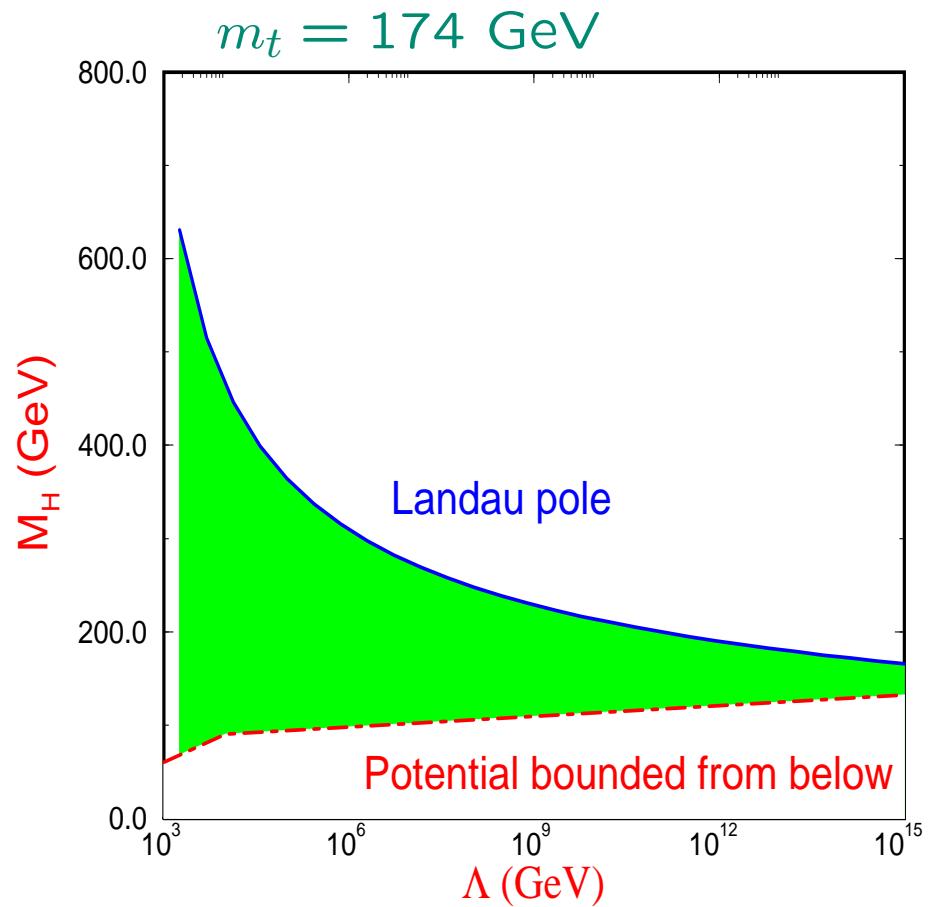
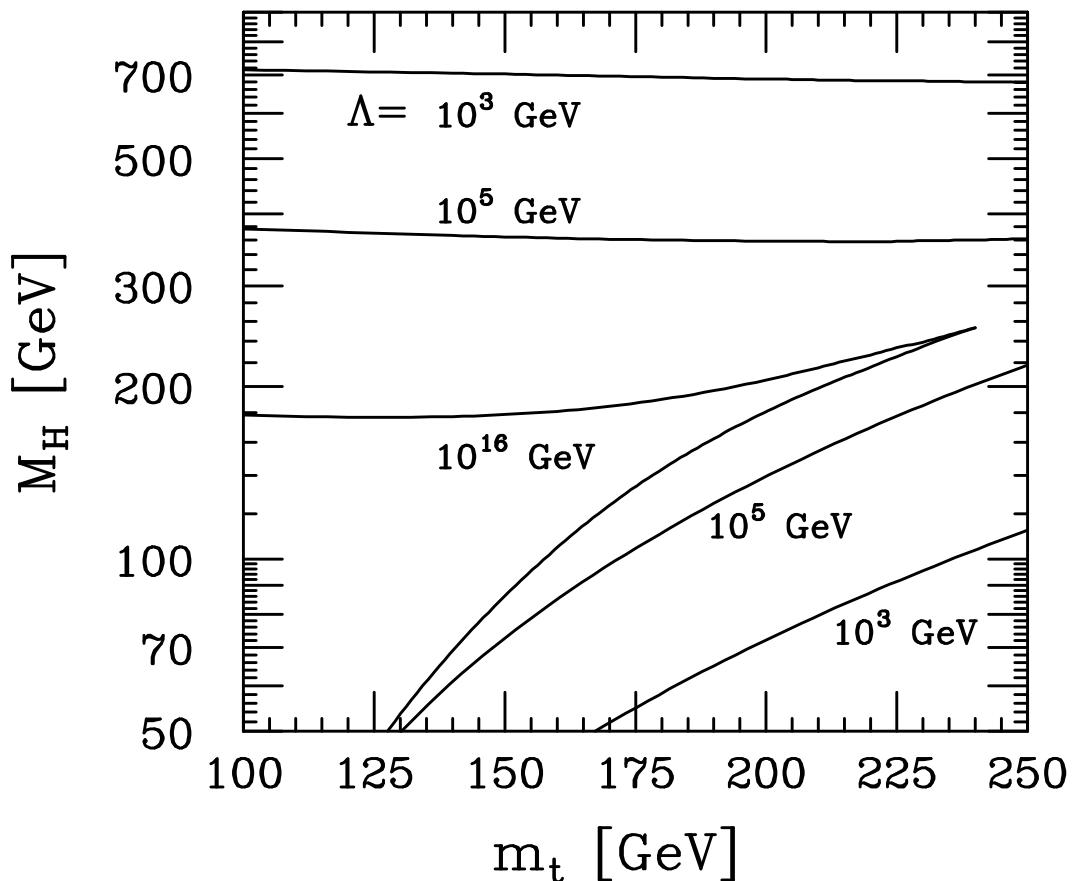
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2} \left[-g_t^4 + \frac{1}{16} (2g_2^4 + (g_2^2 + g_1^2)^2) \right]$$

$$\Rightarrow \lambda(Q^2) = \lambda(v^2) \frac{3}{8\pi^2} \left[-g_t^4 + \frac{1}{16} (2g_2^4 + (g_2^2 + g_1^2)^2) \right] \log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \Rightarrow M_H^2 > \frac{v^2}{4\pi^2} \left[-g_t^4 + \frac{1}{16} (2g_2^4 + (g_2^2 + g_1^2)^2) \right] \log\left(\frac{\Lambda^2}{v^2}\right) : \text{lower bound}$$

Both limits combined:

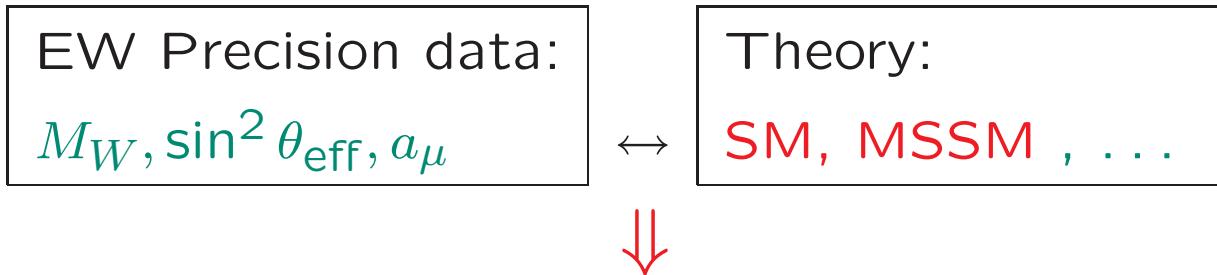


Λ : scale up to which the SM is valid

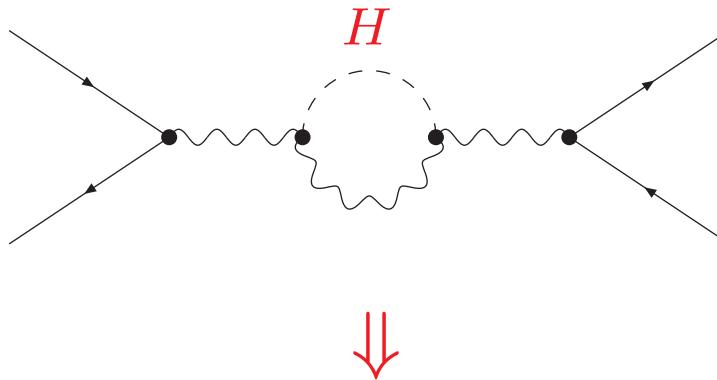
$$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

2. Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: prediction of M_W

Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

⇓
loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\begin{aligned} \Delta r_{\text{1-loop}} &= \Delta \alpha - \frac{c_W^2}{s_W^2} \Delta \rho + \Delta r_{\text{rem}}(M_H) \\ &\sim \log \frac{M_Z}{m_f} \quad \sim m_t^2 \quad \log(M_H/M_W) \\ &\sim 6\% \quad \sim 3.3\% \quad \sim 1\% \end{aligned}$$

Comparison of SM prediction of M_W with direct measurements:

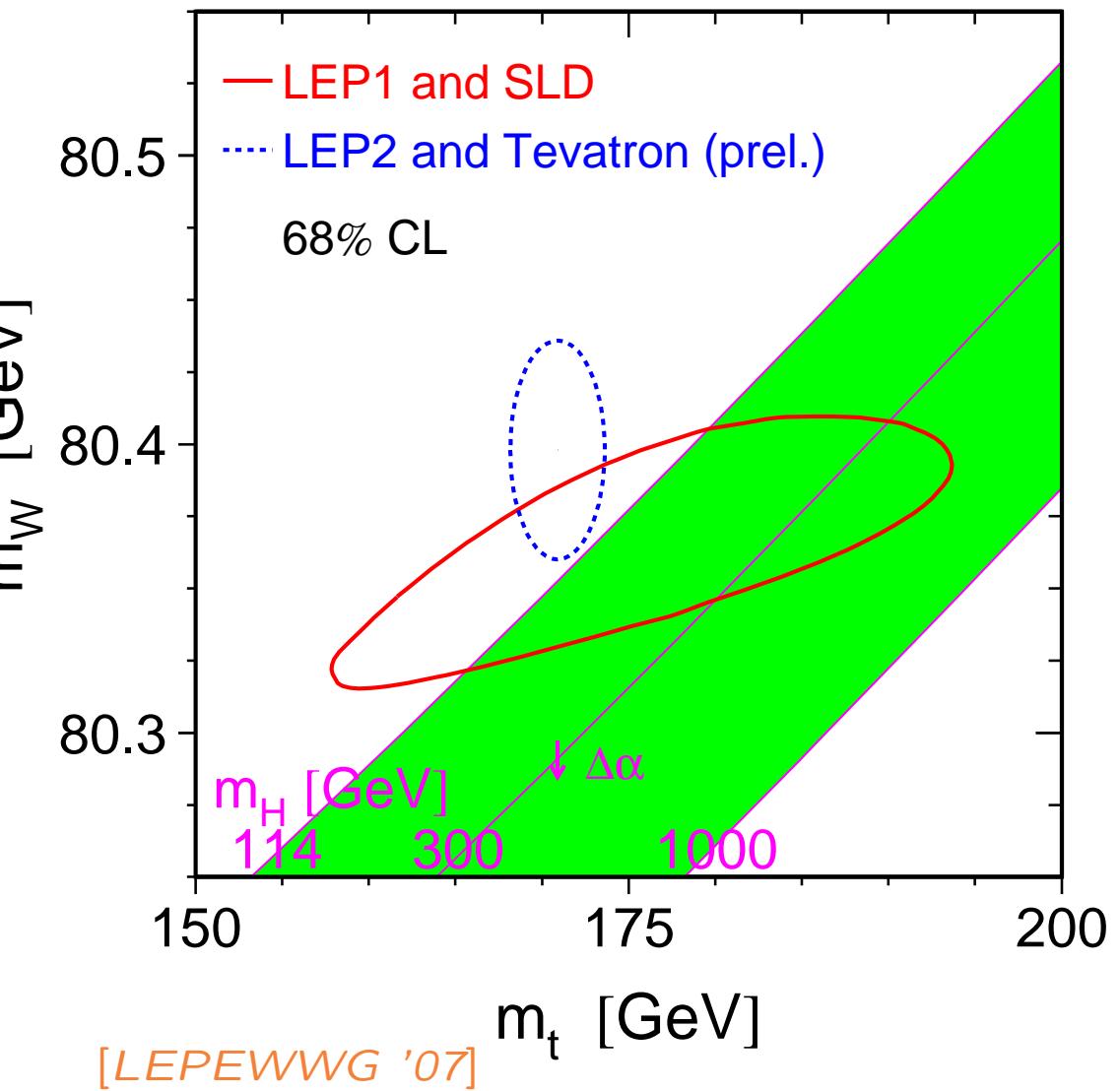
$$\Delta r = -\frac{11g_2^2}{96\pi^2} \frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2} \right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



⇒ light Higgs boson preferred

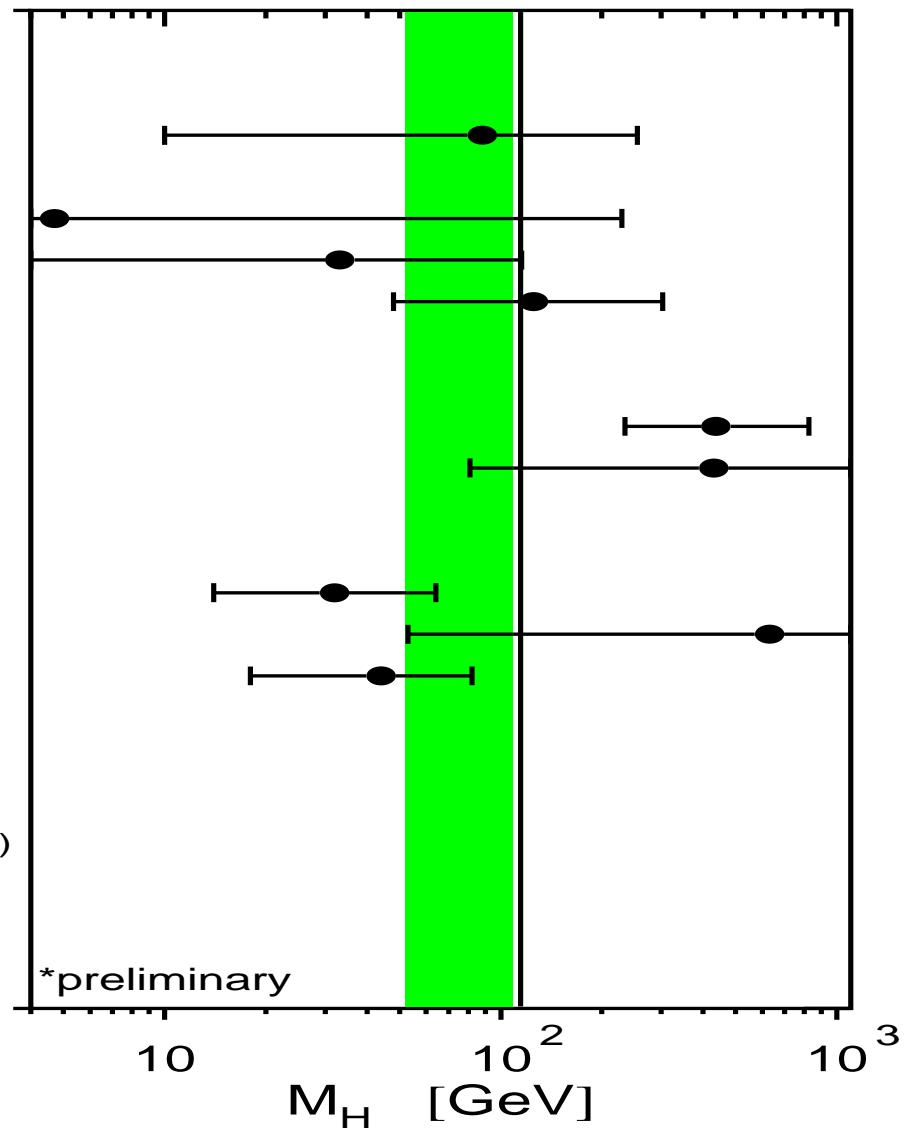
Results for M_H from other EWPO:

light Higgs preferred by:
 M_W , A_l^{LR} (SLD)

heavier Higgs preferred by:
 A_b^{FB} (LEP)
 \Rightarrow keeps SM alive

Γ_Z
 σ_{had}^0
 R_l^0
 $A_{\text{fb}}^{0,\text{l}}$
 $A_l(P_\tau)$
 R_b^0
 R_c^0
 $A_{\text{fb}}^{0,b}$
 $A_{\text{fb}}^{0,c}$
 A_b
 A_c
 $A_l(\text{SLD})$
 $\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$
 m_W^*
 Γ_W^*

 $Q_W(\text{Cs})$
 $\sin^2 \theta_{\overline{\text{MS}}}(\text{e}^- \text{e}^-)$
 $\sin^2 \theta_W(\nu N)$
 $g_L^2(\nu N)$
 $g_R^2(\nu N)$



\Rightarrow light Higgs boson preferred

[LEPEEWG '07]

Global fit to all SM data:

[LEPEWWG '07]

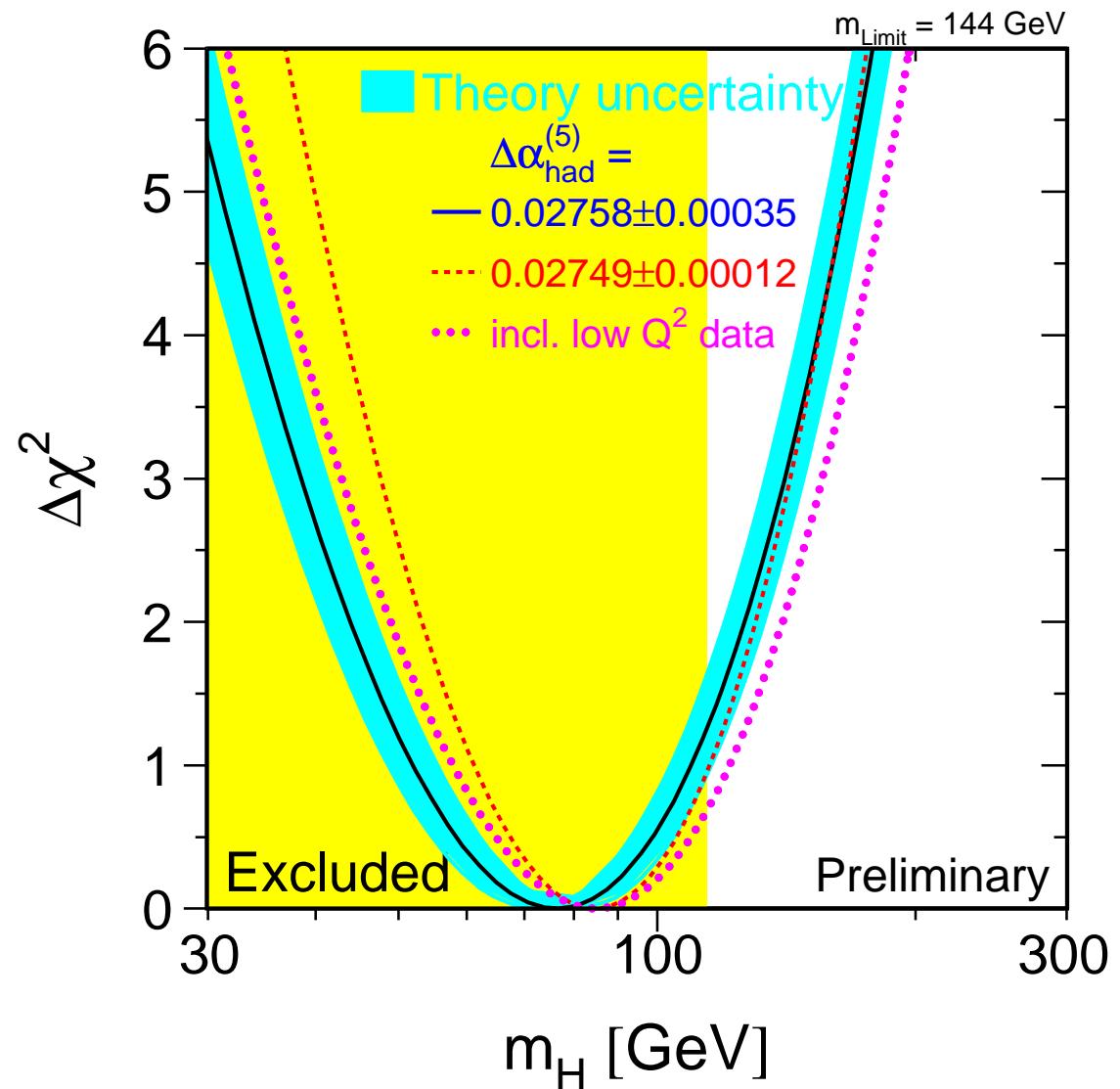
$$\Rightarrow M_H = 76^{+33}_{-24} \text{ GeV}$$

$M_H < 144 \text{ GeV}$, 95% C.L.

Assumption for the fit:

SM incl. Higgs boson

\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Higgs boson seems to be light, $M_H \lesssim 150 \text{ GeV}$

3. Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = [\sqrt{2} G_\mu]^{1/2} m_f$$

decay width:

$$\Gamma(H \rightarrow f\bar{f}) = N_c \frac{G_\mu M_H}{4\sqrt{2}\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \rightarrow m_q^2(M_H^2)$$

Dominant decay process: $H \rightarrow b\bar{b}$

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2 \left[\sqrt{2} G_\mu \right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2M_V$):

$$\Gamma(H \rightarrow VV) = \delta_V \frac{G_\mu M_H^3}{16 \sqrt{2} \pi} \left(1 - 4 \frac{M_V^2}{M_H^2} + 12 \frac{M_V^4}{M_H^4} \right) \left(1 - 4 \frac{M_V^2}{M_H^2} \right)^{1/2}$$

with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2M_V$):

$$\Gamma(H \rightarrow VV^*) = \delta'_V \frac{3G_\mu^2 M_H}{16 \pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg , $\gamma\gamma$):

$$\Gamma(H \rightarrow gg) = \frac{G_\mu \alpha_s^2(M_H^2) \textcolor{teal}{M}_H^3}{36 \sqrt{2} \pi^3} \left[1 + \textcolor{red}{C} \frac{\alpha_s(\mu)}{\pi} \right]$$

via the top quark loop with

$$\textcolor{red}{C} = \frac{215}{12} - \frac{23}{6} \log \left(\frac{\mu^2}{M_H^2} \right) + \mathcal{O}(\alpha_s)$$

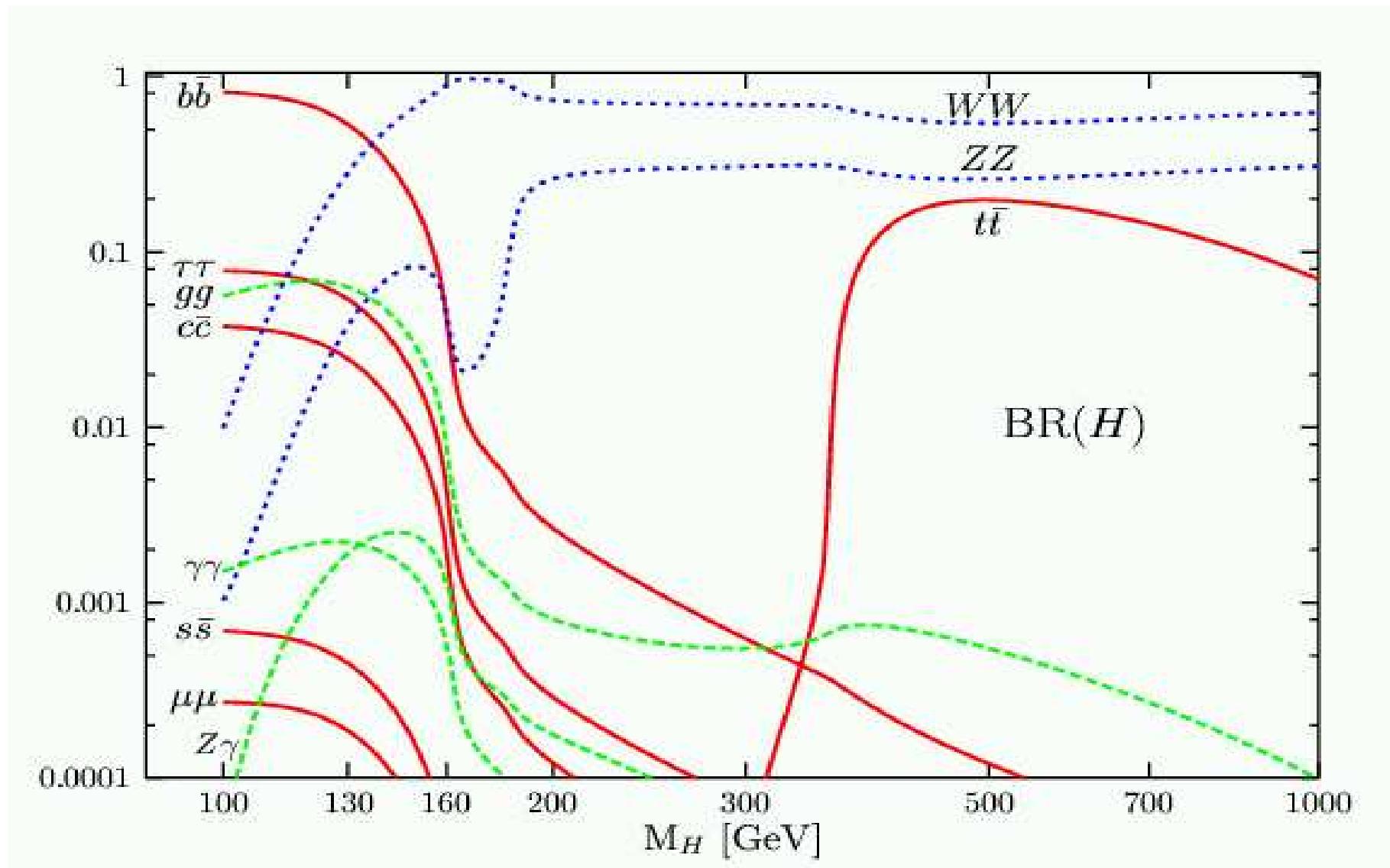
⇒ huge QCD corrections

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_\mu \alpha^2 \textcolor{teal}{M}_H^3}{128 \sqrt{2} \pi^3} \left| \frac{4}{3} e_t^2 - 7 \right|^2$$

via the top quark and W boson loop

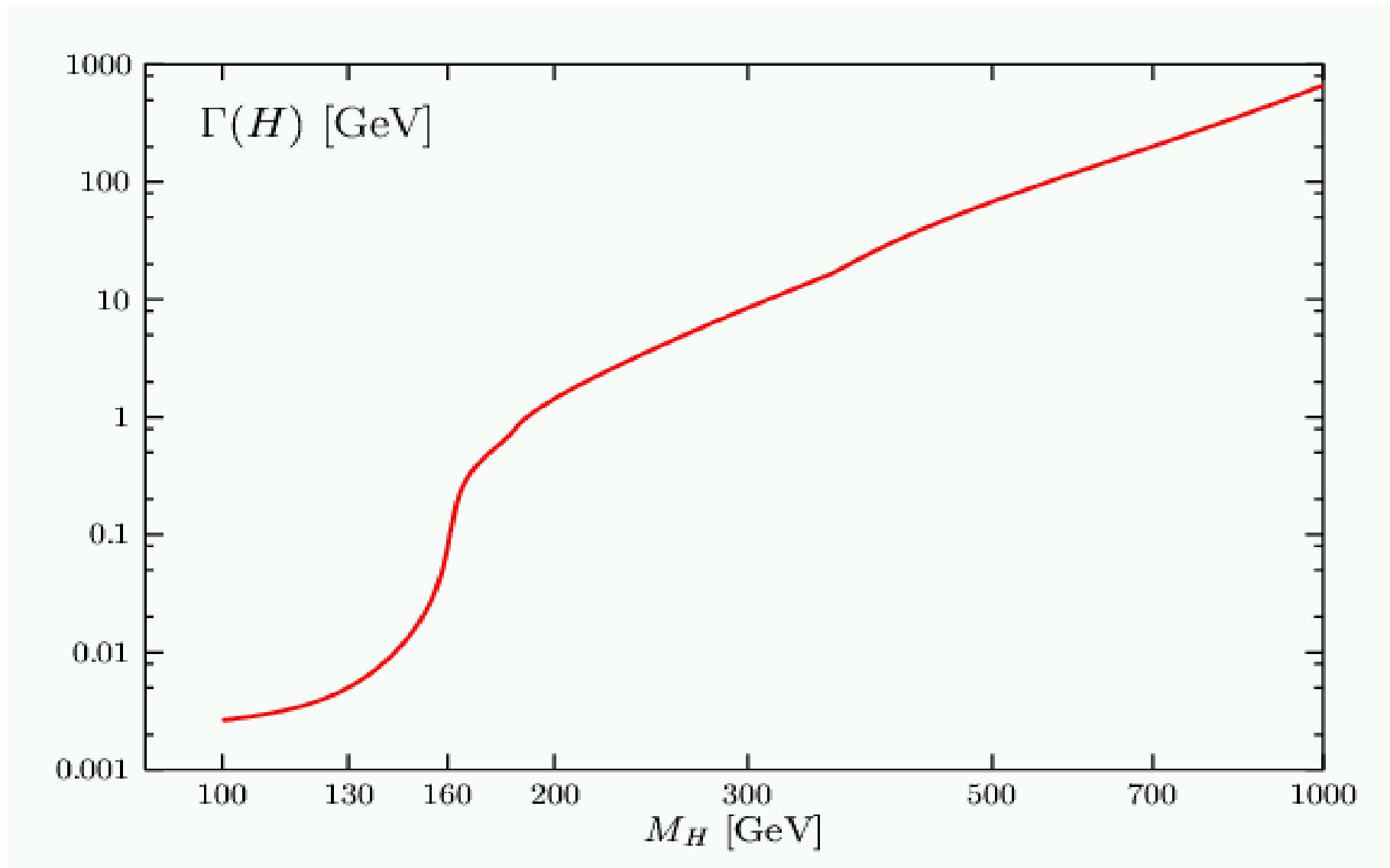
Overview of the branching ratios:

[taken from [hep-ph/0503172](#)]



The total SM Higgs boson width:

[taken from [hep-ph/0503172](#)]



Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass (\Rightarrow ok?)

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4. measure couplings to fermions

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Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass (\Rightarrow ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

1. Find the new particle T
2. measure its mass (\Rightarrow ok?) T
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

T = Tevatron,

Discovering the Higgs boson

What has to be done?

- | | |
|--|-------|
| 1. Find the new particle | T L |
| 2. measure its mass (\Rightarrow ok?) | T L |
| 3. measure coupling to gauge bosons | L |
| 4. measure couplings to fermions | L |
| 5. measure self-couplings | |
| 6. measure spin, . . . | |

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

- | | | | |
|--|---|---|---|
| 1. Find the new particle | T | L | I |
| 2. measure its mass (\Rightarrow ok?) | T | L | I |
| 3. measure coupling to gauge bosons | L | | I |
| 4. measure couplings to fermions | L | | I |
| 5. measure self-couplings | | | I |
| 6. measure spin, . . . | | | I |

T = Tevatron, L = LHC, I = ILC (International Linear e^+e^- collider)

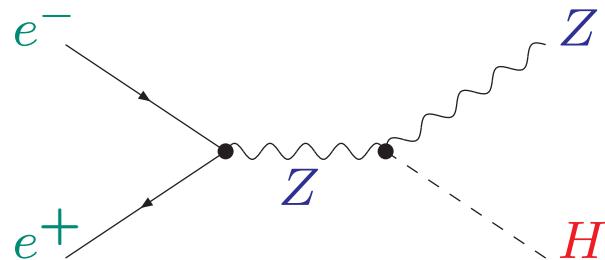
We need the LHC and the ILC to find the Higgs
and to establish the Higgs mechanism!

The LHC can do a crucial part . . .

4. SM Higgs search at LEP:

Dominant production process:

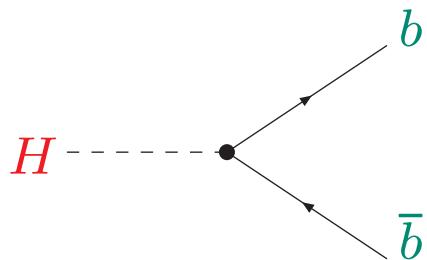
$$e^+ e^- \rightarrow ZH$$



$$\sigma(e^+ e^- \rightarrow ZH) = \frac{G_\mu^2 M_Z^4}{96 \pi s} [v_e^2 + a_e^2] \beta \frac{\beta^2 + 12M_Z^2/s}{(1 - M_Z^2/s)^2}$$

$$\text{with } \beta^2 = (1 - (M_H + M_Z)^2/s)(1 - (M_H - M_Z)^2/s) \quad (1)$$

Dominant decay process: $H \rightarrow b\bar{b}$



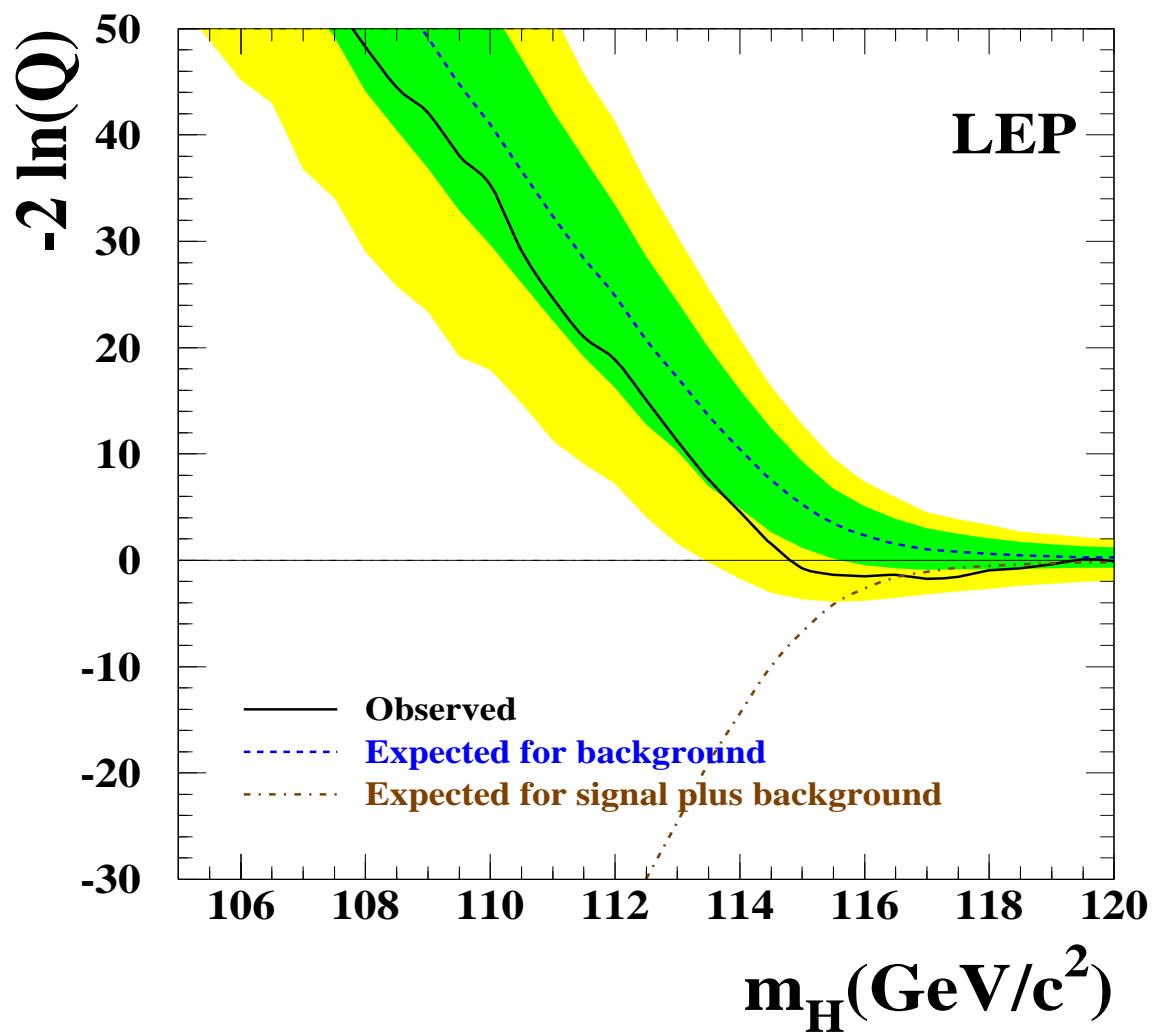
Search for the Standard Model Higgs at LEP: [LEP Higgs WG '03]

Exclusion limit
at the 95% C.L.:

$$M_H > 114.4 \text{ GeV}$$

expected: 115.3 GeV

(LEP has seen **exactly** as many Higgs-like events as could be expected for $M_H \approx 116 \text{ GeV}$, not more, not less)

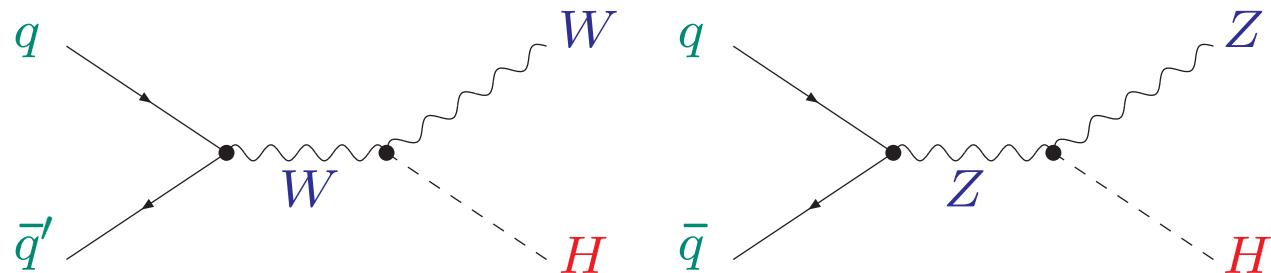


5. SM Higgs search at the Tevatron

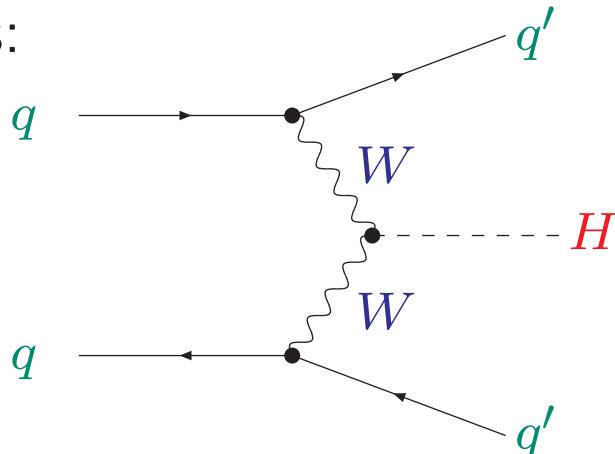
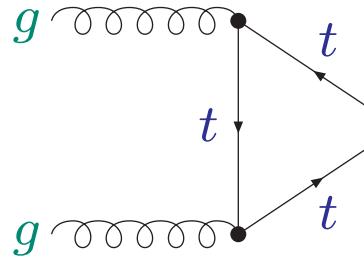
Tevatron: $p\bar{p}$ accelerator:

$\rightarrow \text{T}$

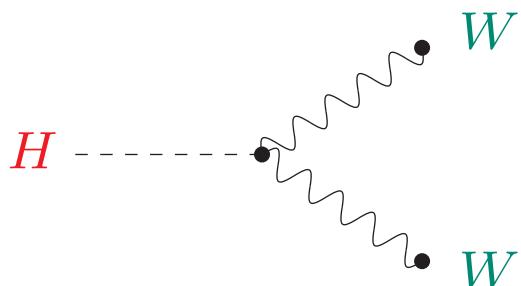
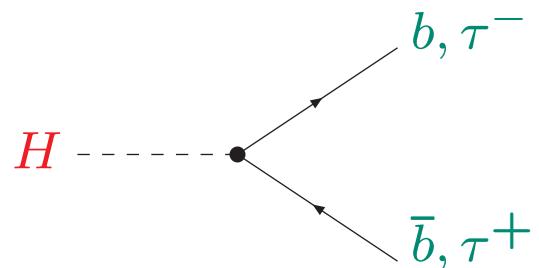
Production processes as at LEP:



Other important production channels:



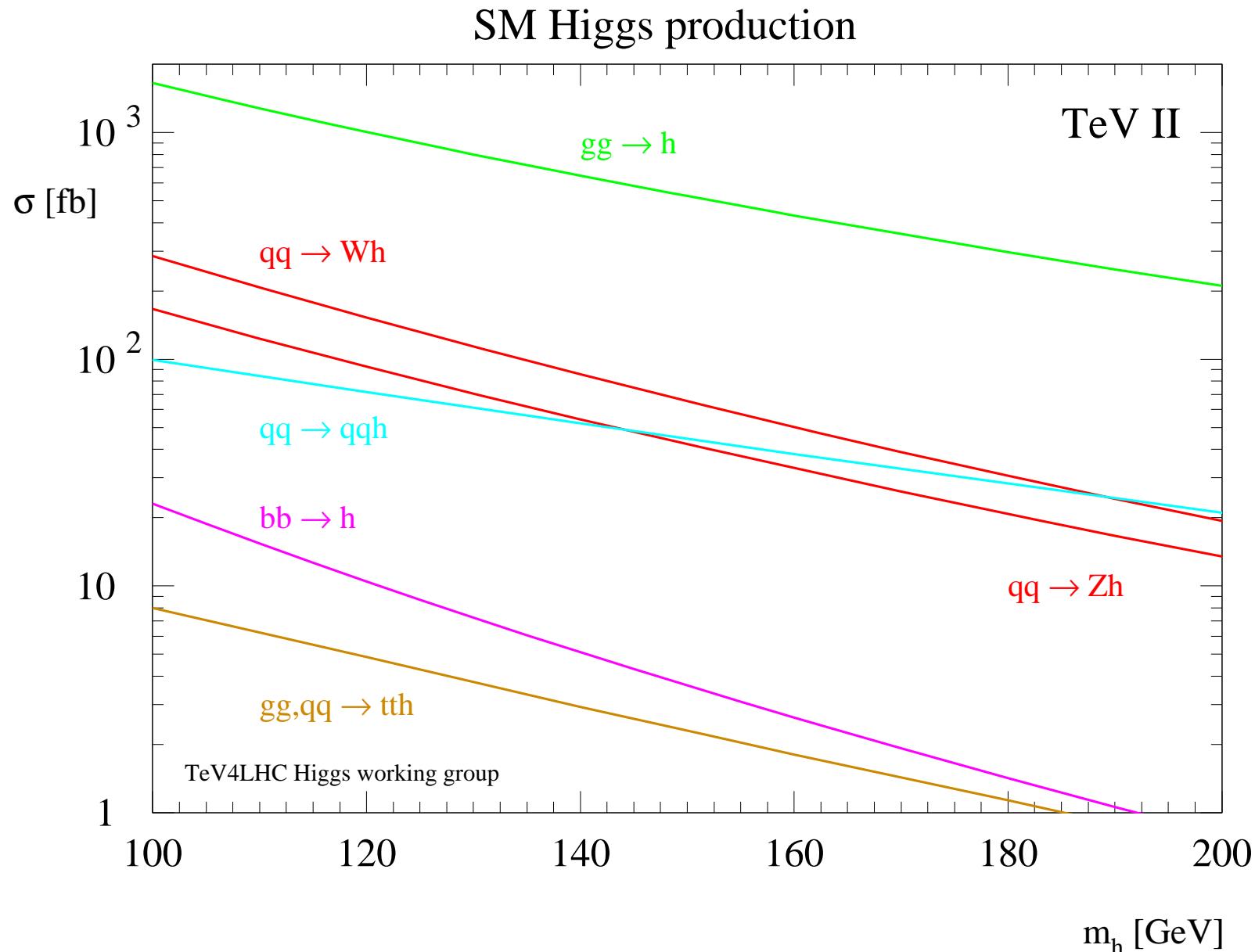
Dominant decays:



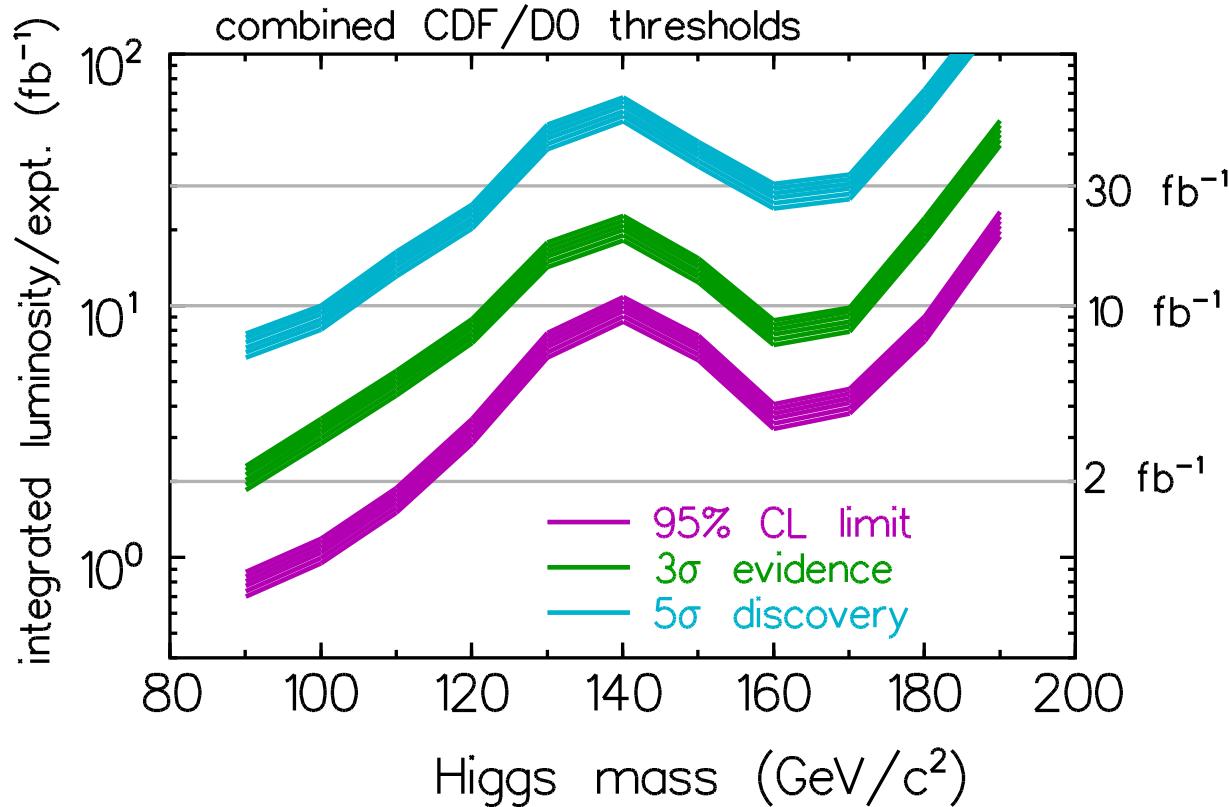


Overview of production cross sections:

[F. Maltoni et al. '05]



Expectations for Higgs discovery at the Tevatron:



Unfortunately: luminosity problems in the start of RunII
⇒ progress slower than anticipated

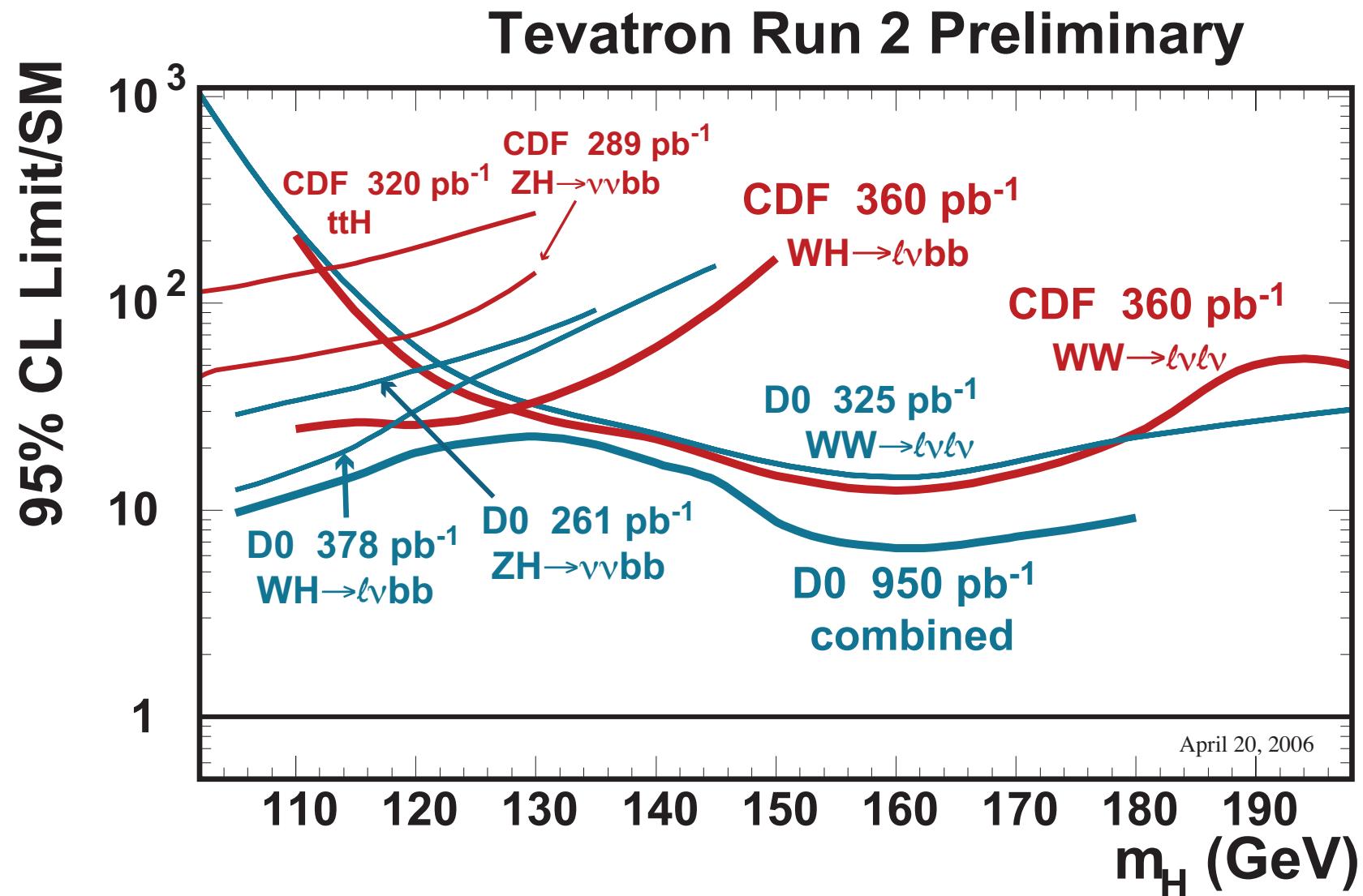
For SM Higgs boson with $M_H \sim 120 \text{ GeV}$:

≈ 2008/09: sensitivity for 95% C.L. exclusion

≈ 2009: sensitivity for 3σ evidence
or exclude SM Higgs with $M_H \lesssim 130 \text{ GeV}$

Results for various search channels for SM Higgs:

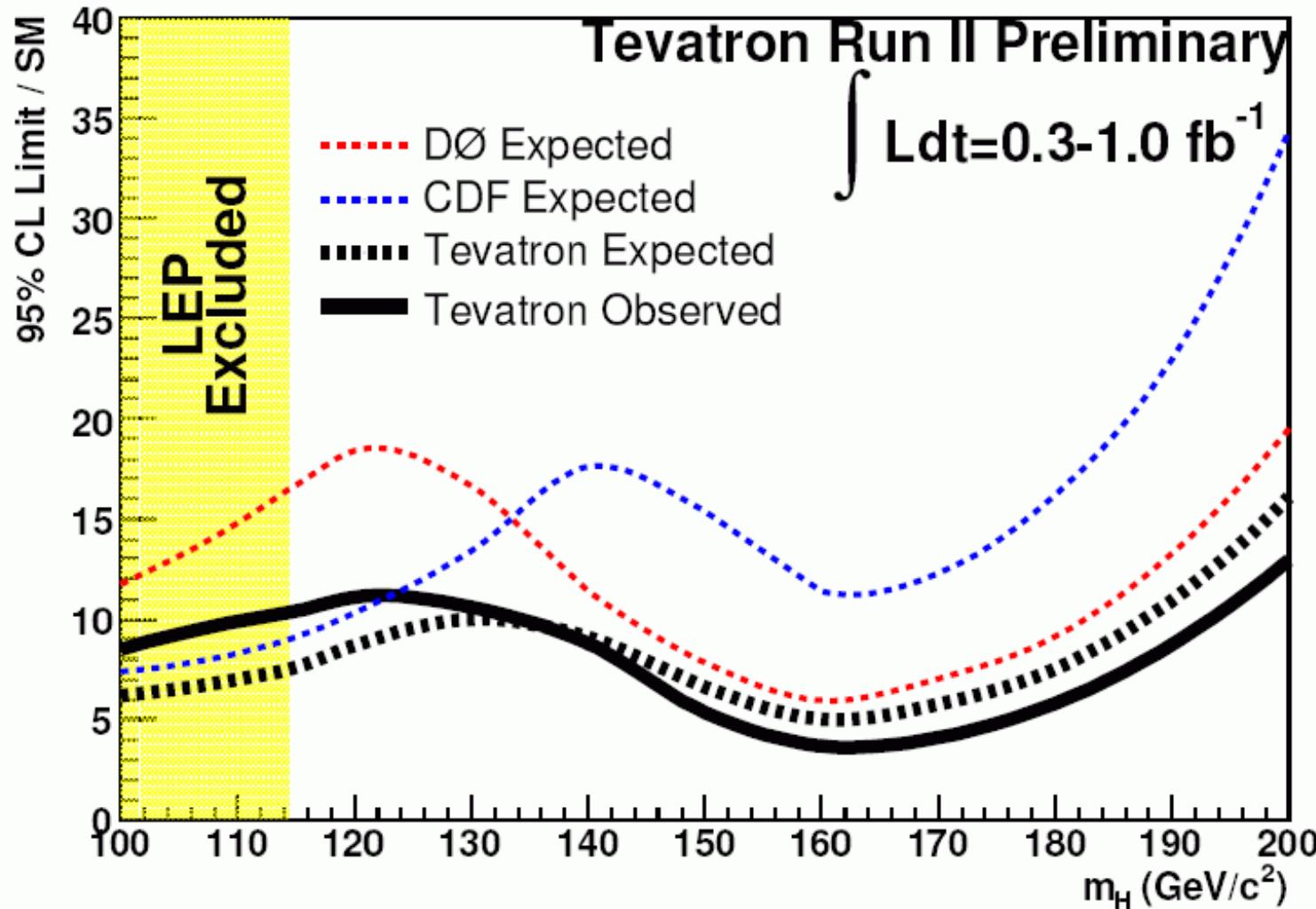
[CDF, D0 '06]



Can they close the gap?

Current status (latest results) of SM Higgs search:

[*CDF, D0 '06*]



Can they close the gap?

6. SM Higgs boson searches at the LHC

LHC: pp accelerator: start: fall 2007

$\rightarrow T$

The (un)official (optimistic?) LHC timeline:

2007 (11/07): fixing the inner triplets

collisions at $\sqrt{s} = 2 \times 450$ GeV canceled

2008: $0.1 \text{ fb}^{-1} - \mathcal{O}(\text{few}) \text{ fb}^{-1}$ (at best) \Rightarrow first physics results?

2009: $\mathcal{O}(\text{few}) \text{ fb}^{-1} \Rightarrow$ first physics results?

2010 – 2012: 10 fb^{-1} per year \Rightarrow physics results with “low” luminosity

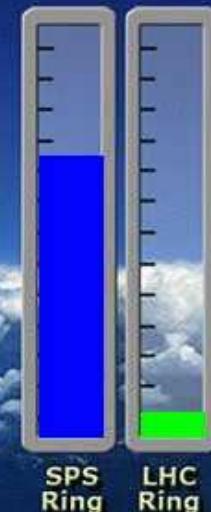
2013 – ?: 100 fb^{-1} per year \Rightarrow physics results with “high” luminosity

2015 + X ($X > 0$): upgrade to SLHC?

LHC: The Large Hadron Collider

The protons have not yet been accelerated to their full energy.

You need to supply more energy by raising the accelerator handle...



6. SM Higgs boson searches at the LHC

LHC: pp accelerator: start: fall 2007

The (un)official (optimistic?) LHC timeline:

2007 (11/07): fixing the inner triplets

collisions at $\sqrt{s} = 2 \times 450$ GeV canceled

2008: 0.1 fb^{-1} – $\mathcal{O}(\text{few}) \text{ fb}^{-1}$ (at best) \Rightarrow first physics results?

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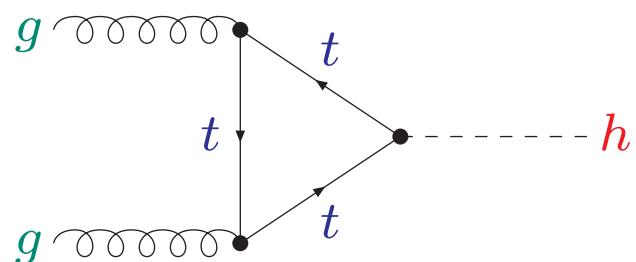
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YOU live in an exciting time!!!

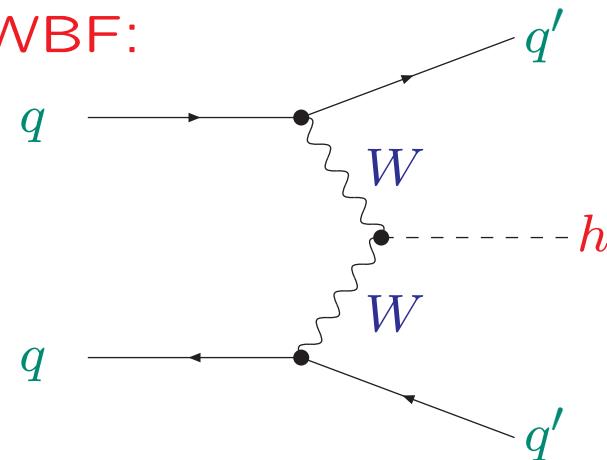
Examples for Higgs production and decay at the LHC:

Important production channel at the LHC:

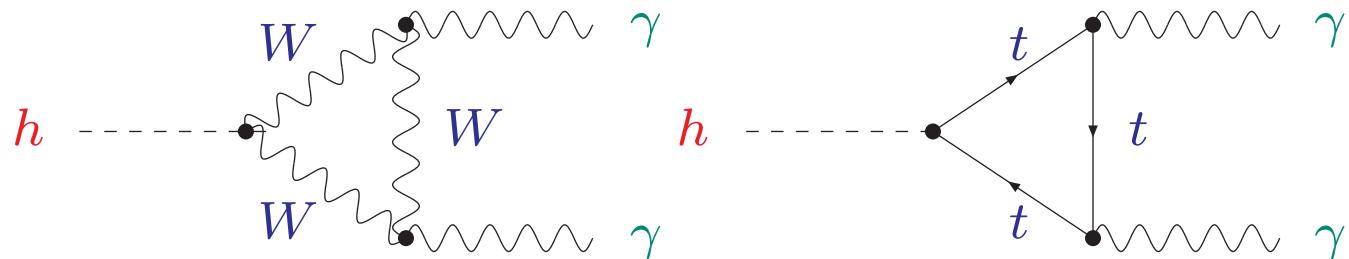
Gluon-Fusion:



WBF:

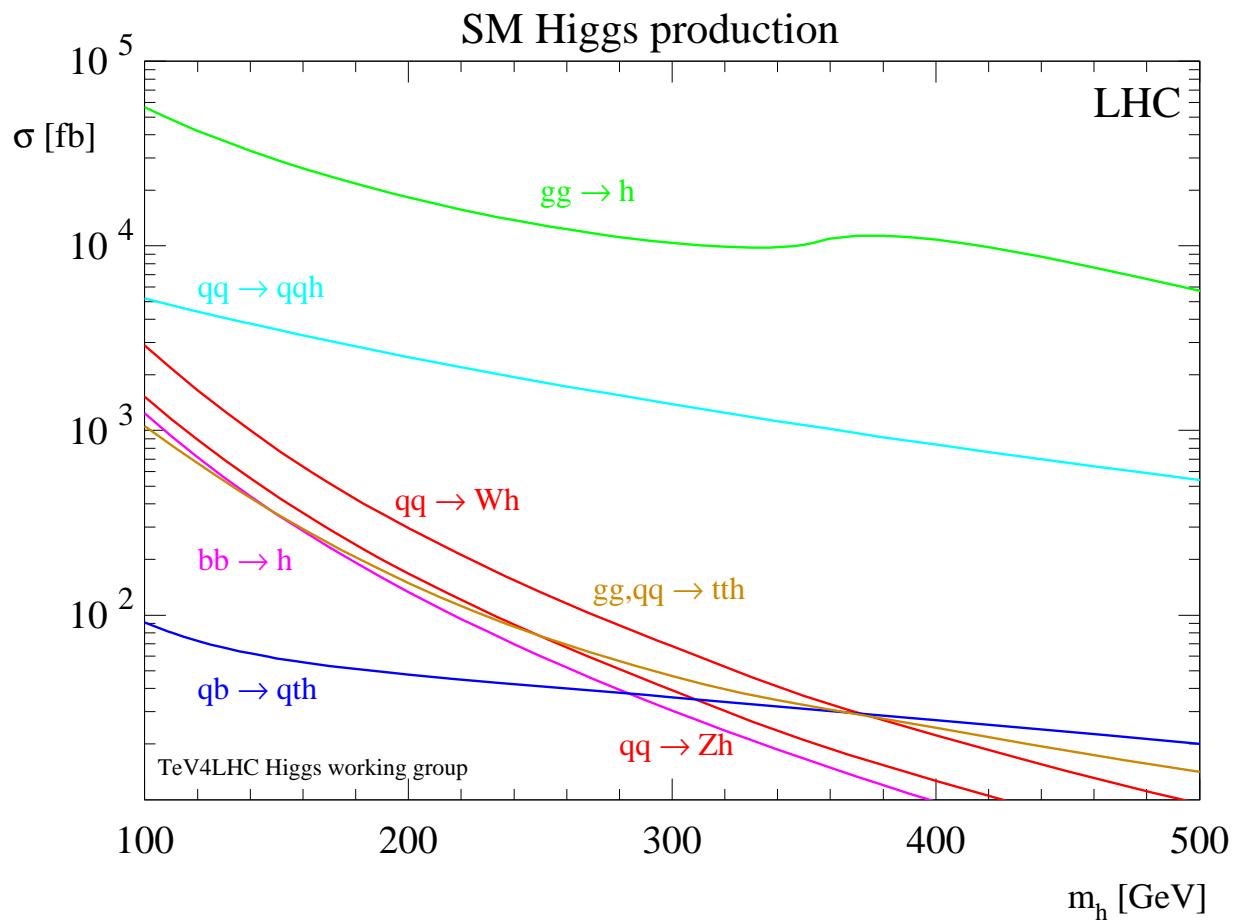


Important decay for Higgs mass measurement:



Step 1: Discovery of the new particle

SM Higgs production at the LHC:



gluon fusion: $gg \rightarrow H$

weak boson fusion (WBF):
 $q\bar{q} \rightarrow q'\bar{q}'H$

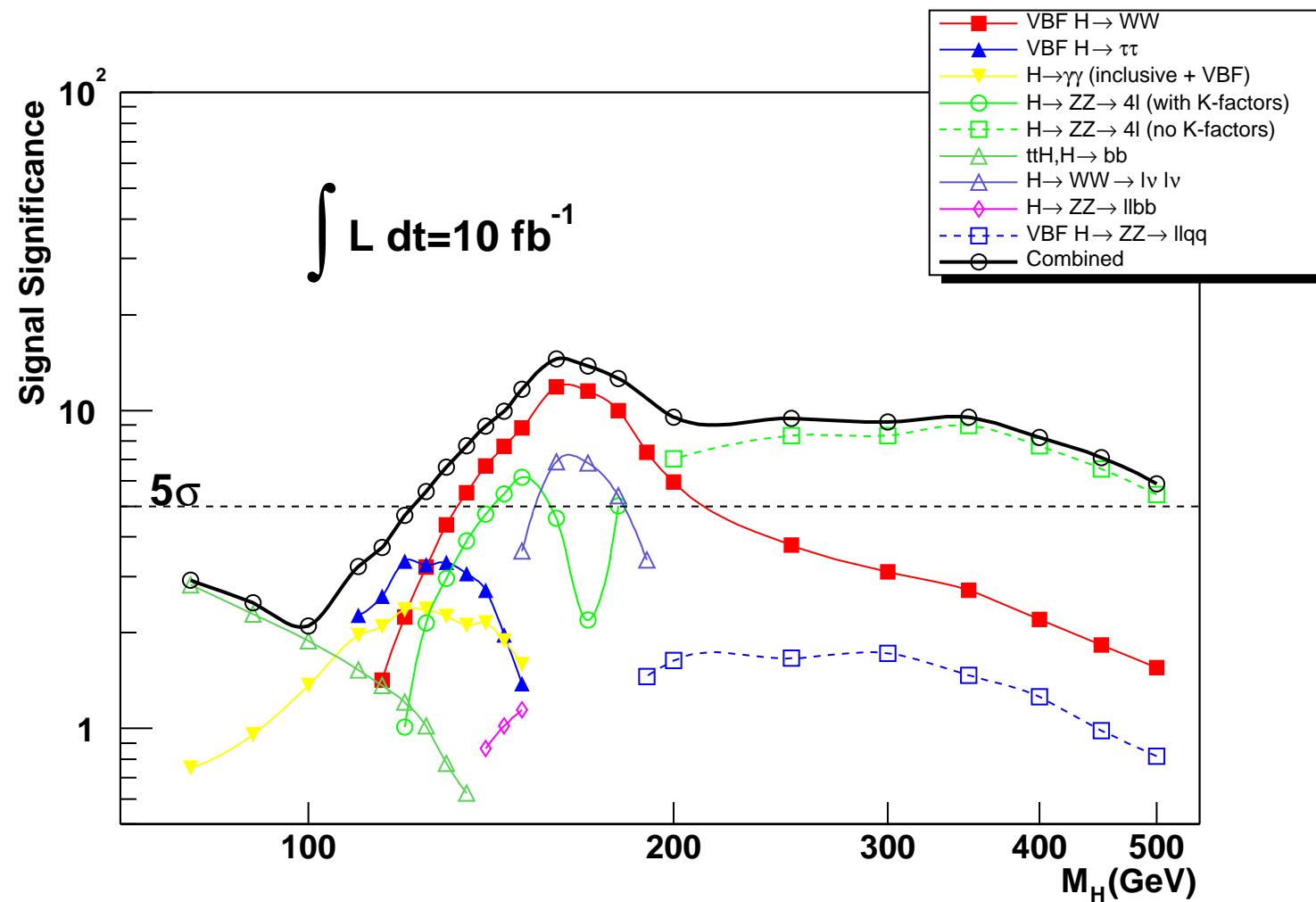
top quark associated
production: $gg, q\bar{q} \rightarrow t\bar{t}H$

weak boson associated
production: $q\bar{q}' \rightarrow WH, ZH$

SM Higgs search at the LHC: \Rightarrow full parameter space accessible

SM Higgs search at the LHC: \Rightarrow full parameter space accessible

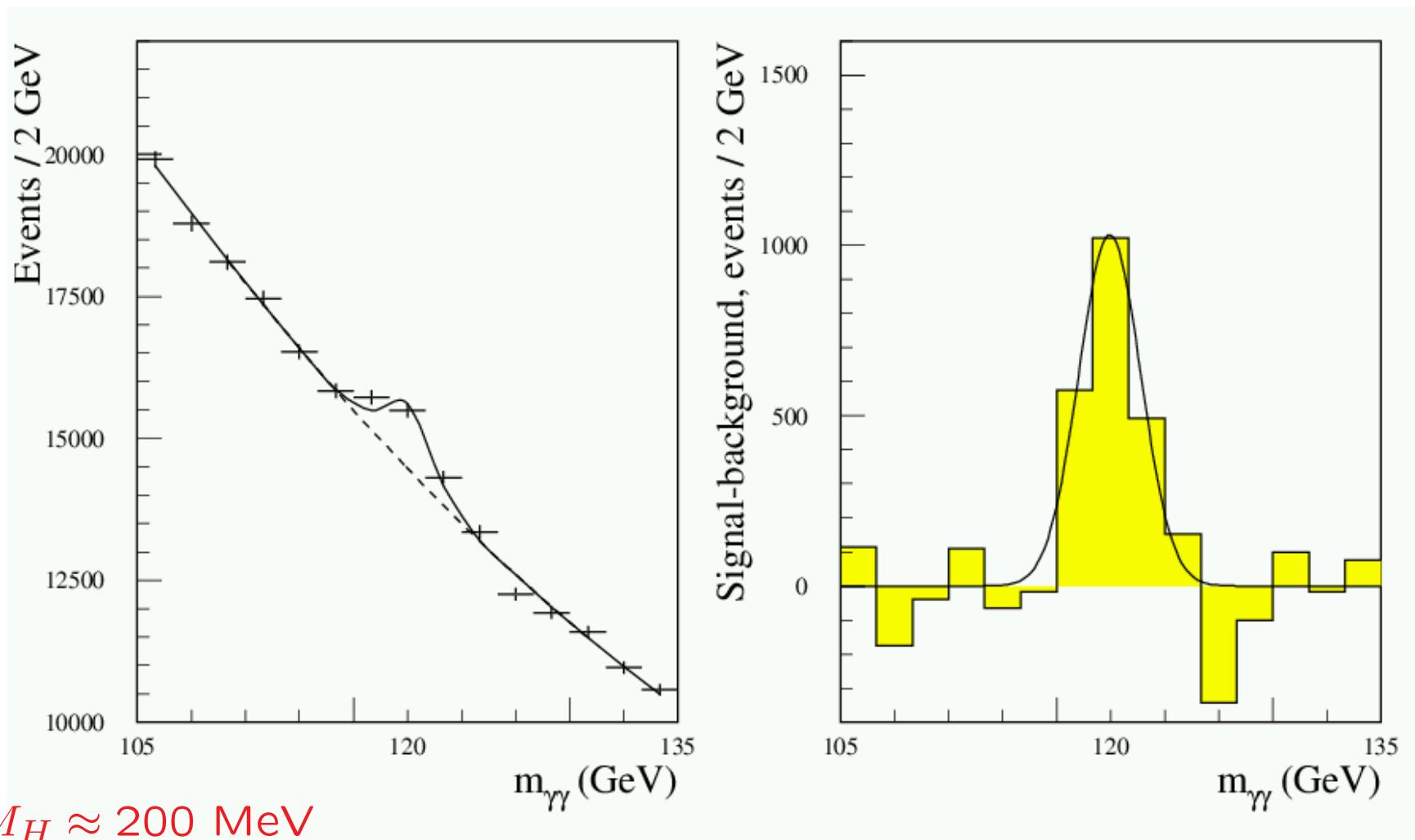
[ATLAS '05]



Step 2: Measurement of the mass

Best channel for mass measurement in the SM: $H \rightarrow \gamma\gamma$

[ATLAS '99]



Step 3, 4: measurement of couplings to gauge bosons and fermions

Measurements for a SM Higgs (or SM-like MSSM Higgs) at the LHC:

Measurement of $\sigma \times \text{BR}$: "narrow width" approximation:

$$\Rightarrow \sigma(H) \times \text{BR}(H \rightarrow xx) = \sigma(H)^{\text{SM}} \cdot \frac{\Gamma_{\text{prod}}}{\Gamma_{\text{prod}}^{\text{SM}}} \times \frac{\Gamma_{\text{partial}}}{\Gamma_{\text{tot}}}$$

Observation of different channels

\Rightarrow Information about combinations of $\Gamma_b, \Gamma_\tau, \Gamma_W, \Gamma_Z, \Gamma_g, \Gamma_\gamma, Y_t^2$

\Rightarrow Additional theory assumptions necessary for absolute determination of partial widths

Only assumption:

\rightarrow consider general multi Higgs-Doublet model
w/o additional Higgs-Singlets
(\Rightarrow includes e.g. MSSM)

\Rightarrow Absolute Determination of Γ_{tot} and Higgs couplings in a global fit
 \Rightarrow (nearly) model independent analysis

Luminosity at the LHC:

- $2 * 30 \text{ fb}^{-1}$: 30 fb^{-1} in each of the two experiments
- $(2*300+2*100) \text{ fb}^{-1}$: 300 fb^{-1} in each experiment, but only 100 fb^{-1} usable for gauge boson fusion

Estimate of errors:

1.) Statistical errors:

Assumption: **SM rates** for production and decay in all scenarios

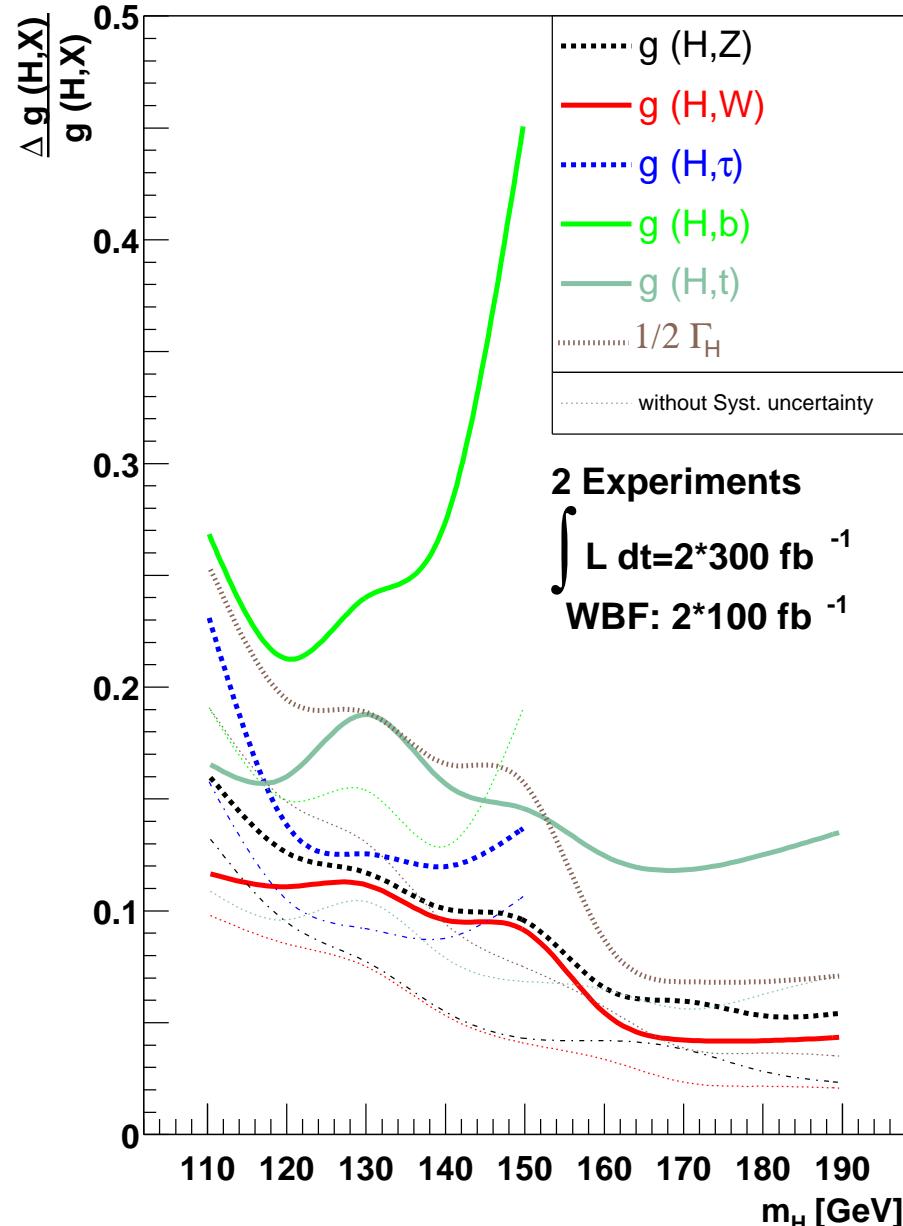
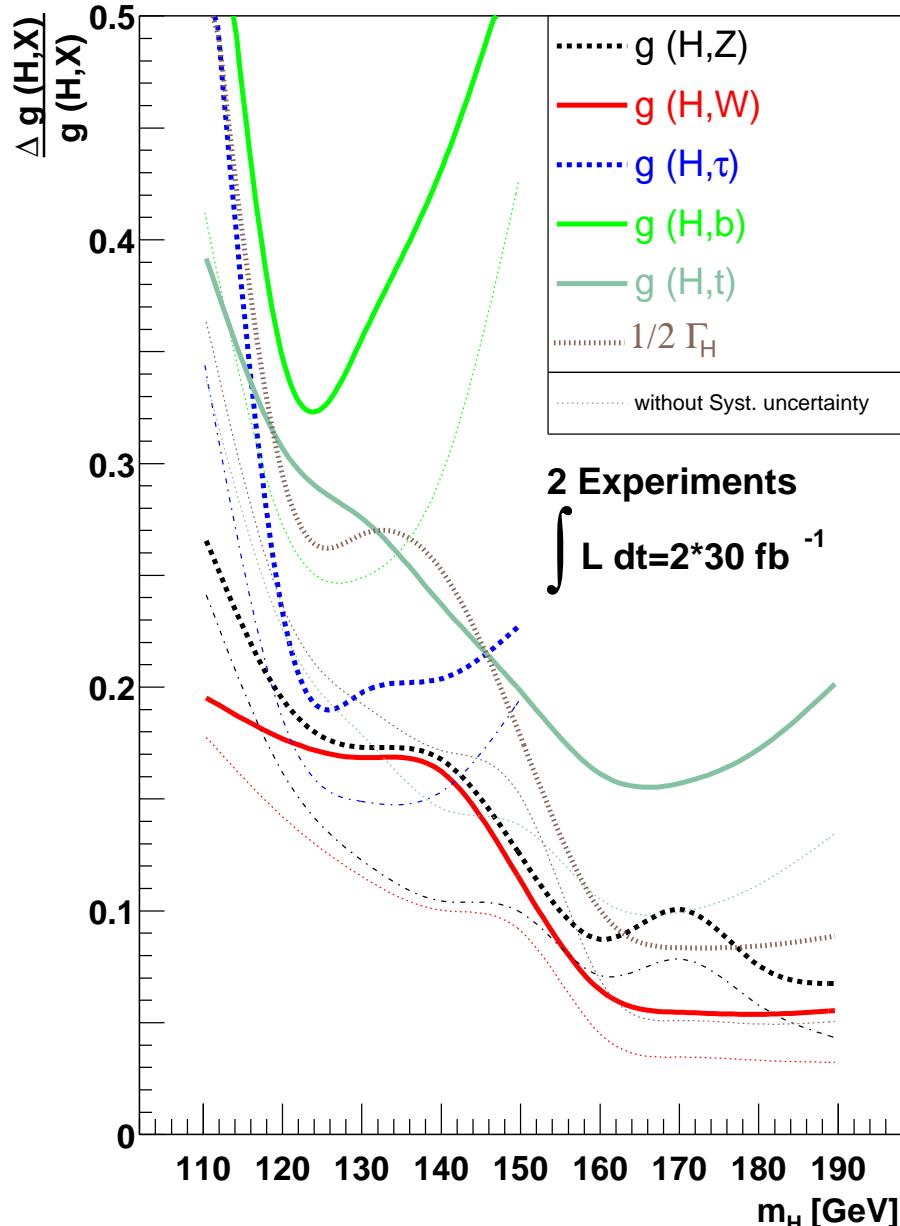
2.) Systematic errors:

→ attempt to include realistically all possible errors

⇒ “log likelihood” function,
based on statistical and systematic errors

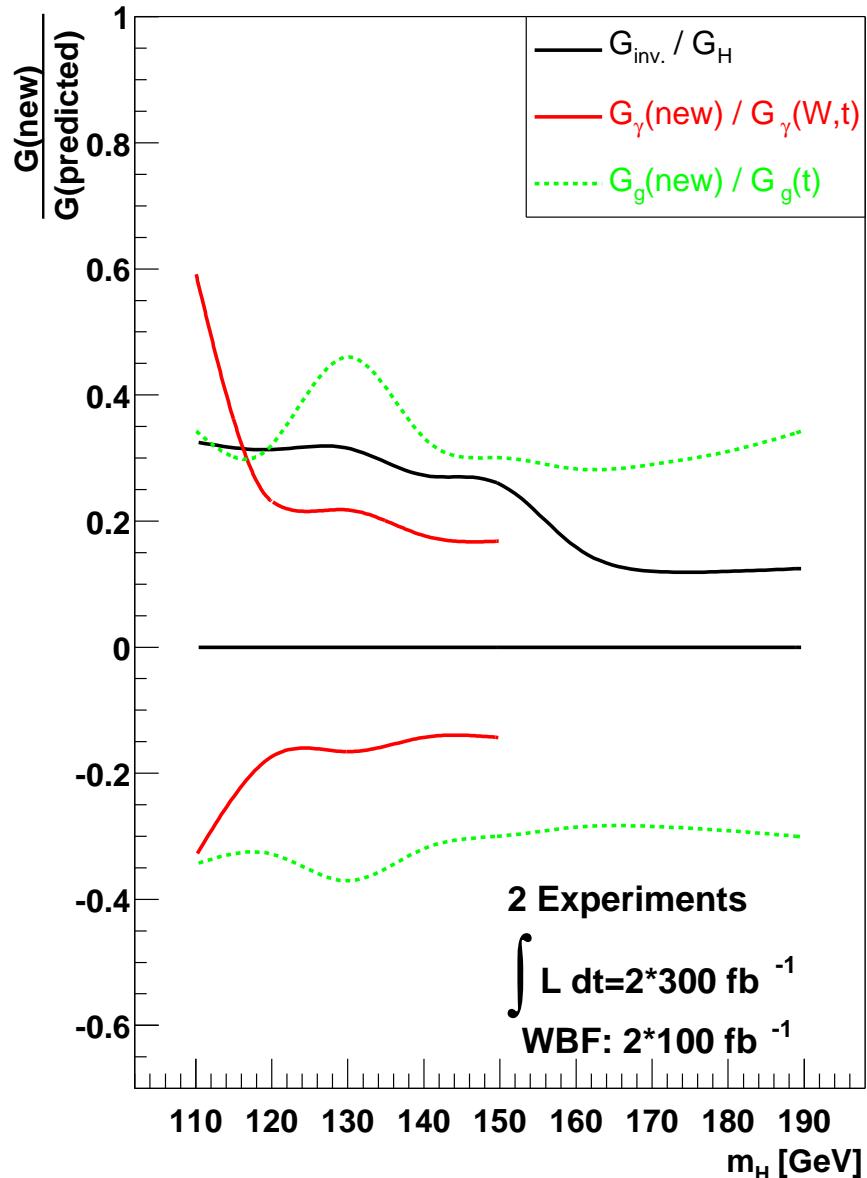
Relative precision for partial and total Higgs widths: two scenarios

[M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04]



Constraints on extra partial widths:

[M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04]



measurement of SM rates
⇒ constraints on widths:

$(2 * 300 + 2 * 100) \text{ fb}^{-1}$ scenario:

$$\Delta \Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\text{SM}}$$

$$\Delta \Gamma_g \leq 0.4 \times \Gamma_g^{\text{SM}}$$

$$\Delta \Gamma_{\text{inv}} \leq 0.2 \times \Gamma_{\text{tot}}^{\text{SM}}$$

⇒ restrictions on new physics!

Results:

Absolute determination of Higgs couplings is possible!

Scenario with low luminosity: $2 * 30 \text{ fb}^{-1}$:

for a light Higgs: results significantly worse in comparison with higher luminosity

Scenario with higher luminosity: $(2 * 300 + 2 * 100) \text{ fb}^{-1}$:

- typical precision of 15-25% for $m_H \lesssim 150 \text{ GeV}$
- 5% accuracy for HVV couplings above WW threshold

Systematic errors contribute about 50% to the total error, especially at high luminosity

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What happens with non-SM rates?

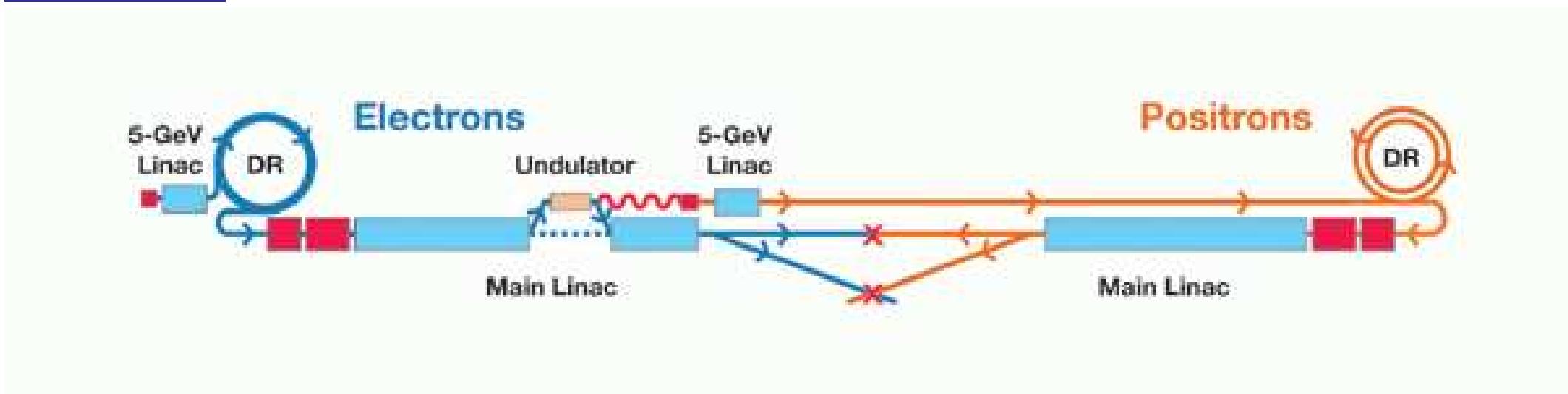
⇒ not analyzed yet . . .

7. SM Higgs boson precision physics at the ILC

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

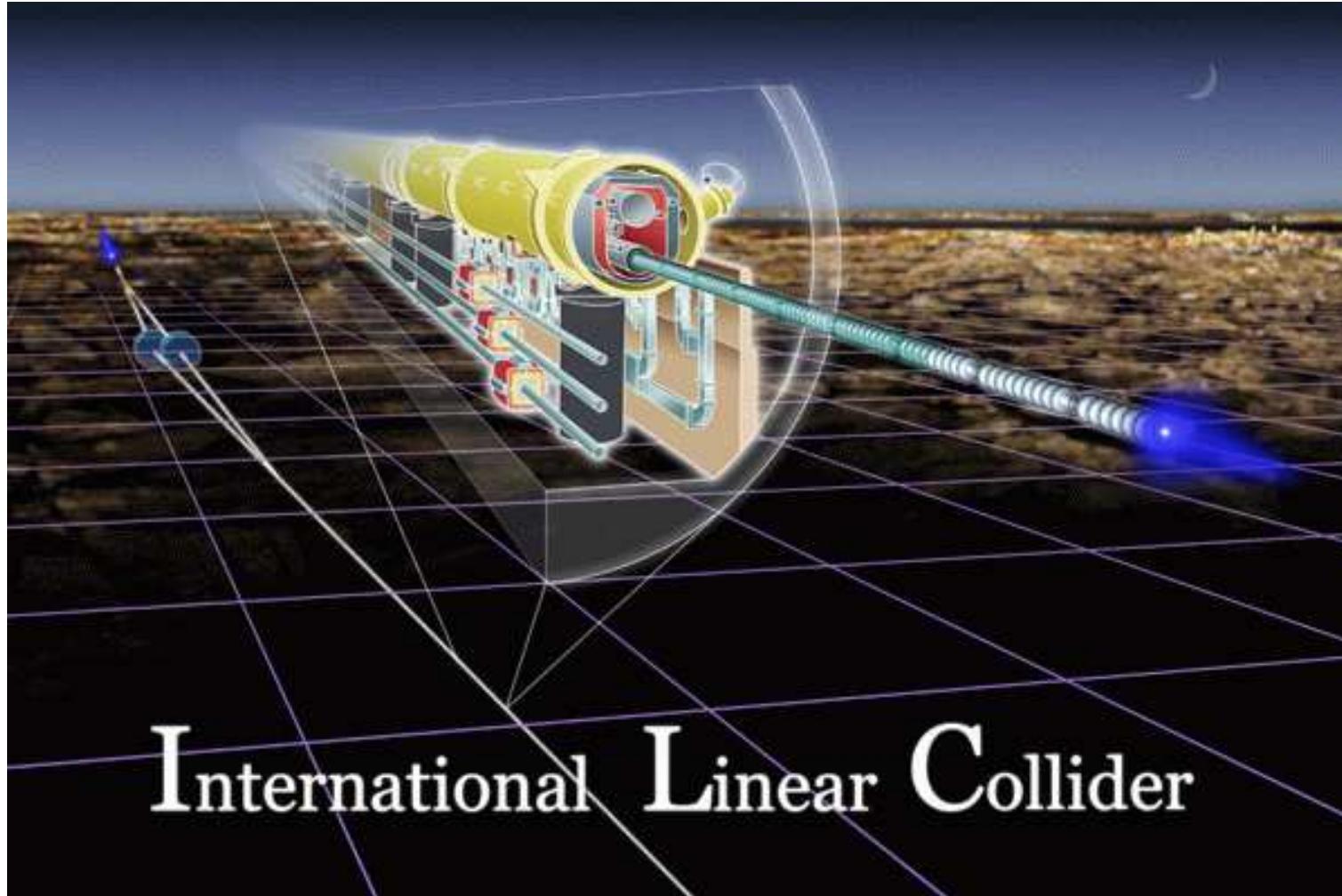
based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



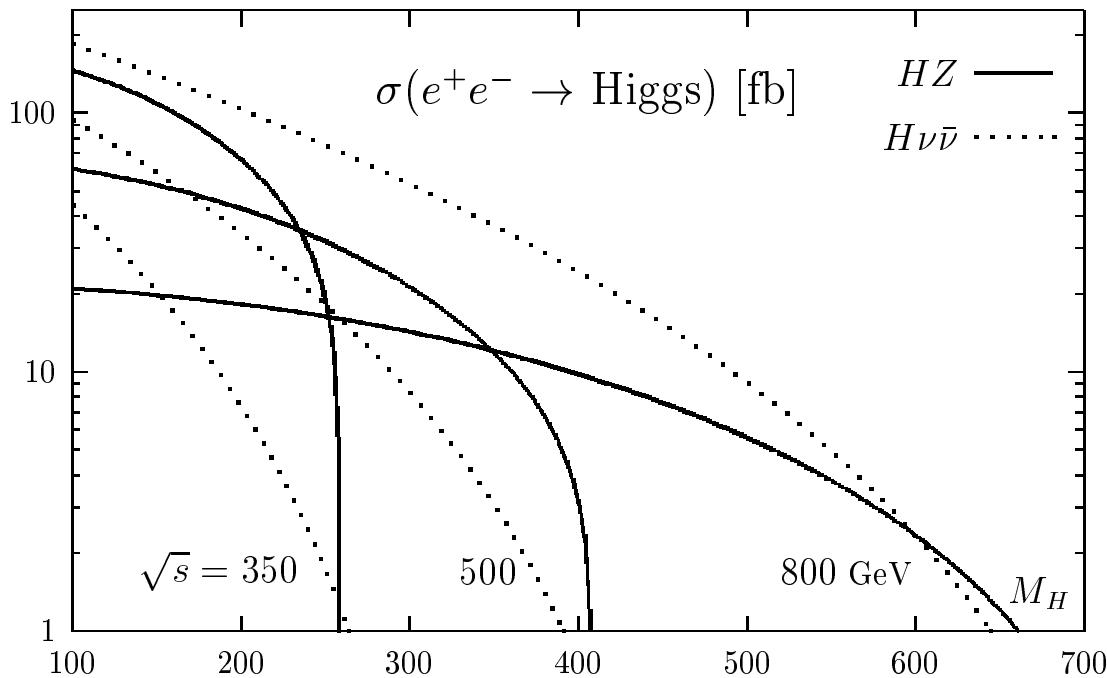
- 2 interaction regions (one without(?), one with crossing angle)
- undulator based e^+ source
- polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

The tunnel and the tubes:

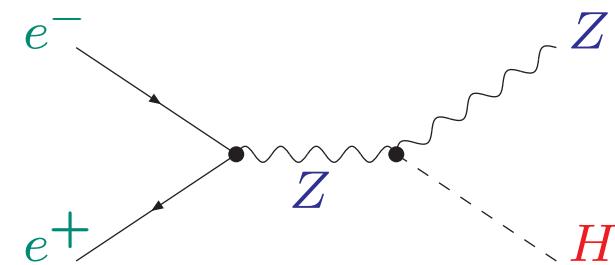


International Linear Collider

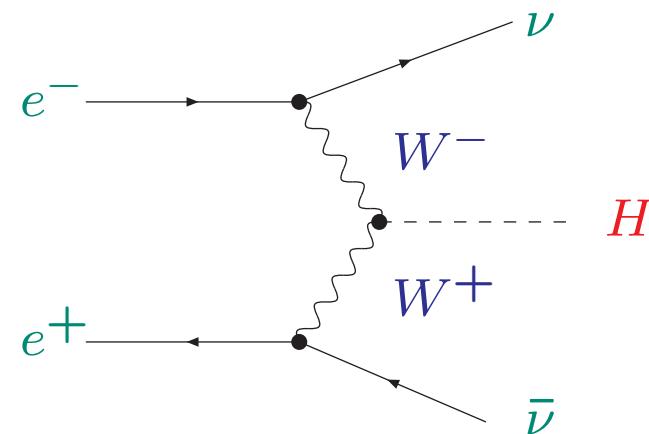
Higgs production at the ILC:



Higgs-strahlung:
 $e^+e^- \rightarrow Z^* \rightarrow ZH$



weak boson fusion (WBF):
 $e^- + e^- \rightarrow \nu\bar{\nu}H$



⇒ Measurement of masses, couplings, ... in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \rightarrow ZH$, $Z \rightarrow e^+e^-$, $\mu^+\mu^-$

⇒ total measurement of Higgs production cross section

⇒ NO additional theoretical assumptions needed for absolute determination of partial widths

⇒ all observable channels can be measured with high accuracy

Some ILC results (500 fb⁻¹ @ $\sqrt{s} = 350$ GeV):

$$\delta M_H \approx 50 \text{ MeV}$$

$$\delta g_{ZZH} \approx 2.5\%, \quad \delta g_{WWH} \approx 2 - 5\%$$

$$\delta g_{Hb\bar{b}} \approx 1 - 2\% \text{ (for } M_H \lesssim 150 \text{ GeV)}$$

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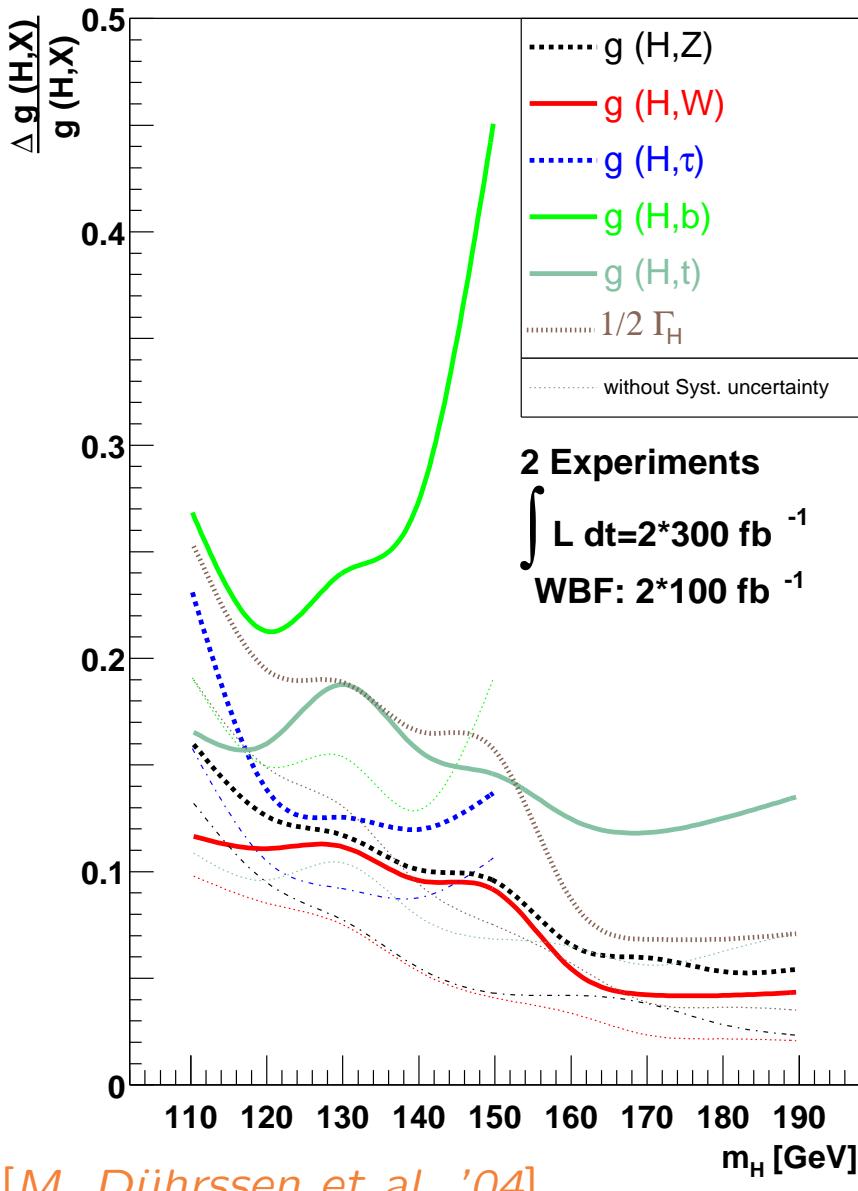
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How does this compare to the LHC?

The LHC will find a Higgs and measure its characteristics:



- mass: $\delta M_h \approx 200 \text{ MeV}$
- couplings: $(2 * 300 + 2 * 100) \text{ fb}^{-1}$: typical accuracies of 20-30% for $m_H \leq 150 \text{ GeV}$
10% accuracies for HVV couplings above WW threshold

Assumption:

- $g_{HVV}^2 \leq g_{HVV,SM}^2 \times 1.05$
- SM rates for the Higgs

Problems:

- valid in weakly interacting models
- rates much lower than in SM ??
- physics can/will hide in 5% margin
- self-couplings out of reach

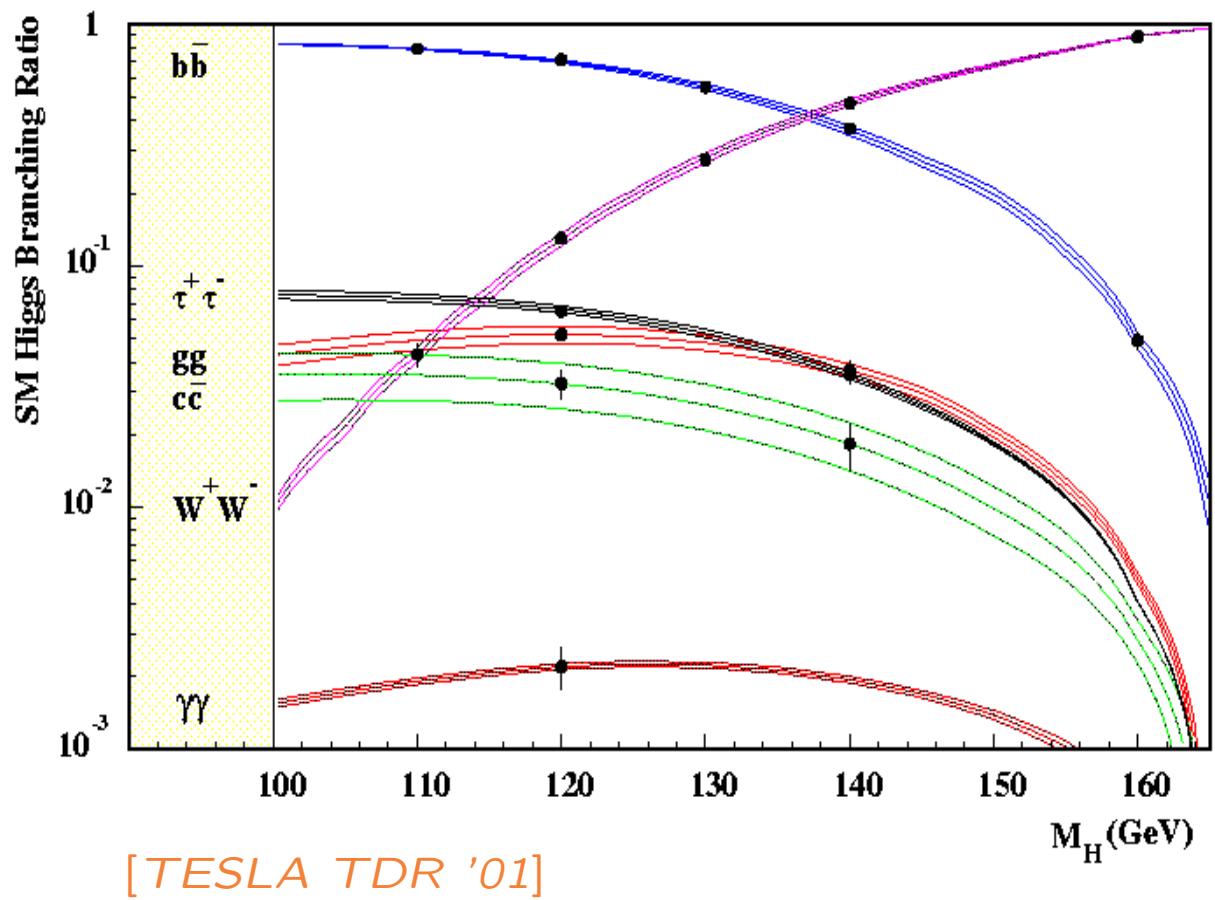
⇒ ILC comes in

Compare to the ILC:

SM Higgs @ ILC:

Precise measurement of:

1. Higgs boson mass,
 $\delta M_H \approx 50 \text{ MeV}$
2. Higgs boson width
(direct/indirect)
3. Higgs boson couplings,
 $\mathcal{O}(\text{few}\%)$ \Rightarrow
4. Higgs boson quantum
numbers: spin, . . .

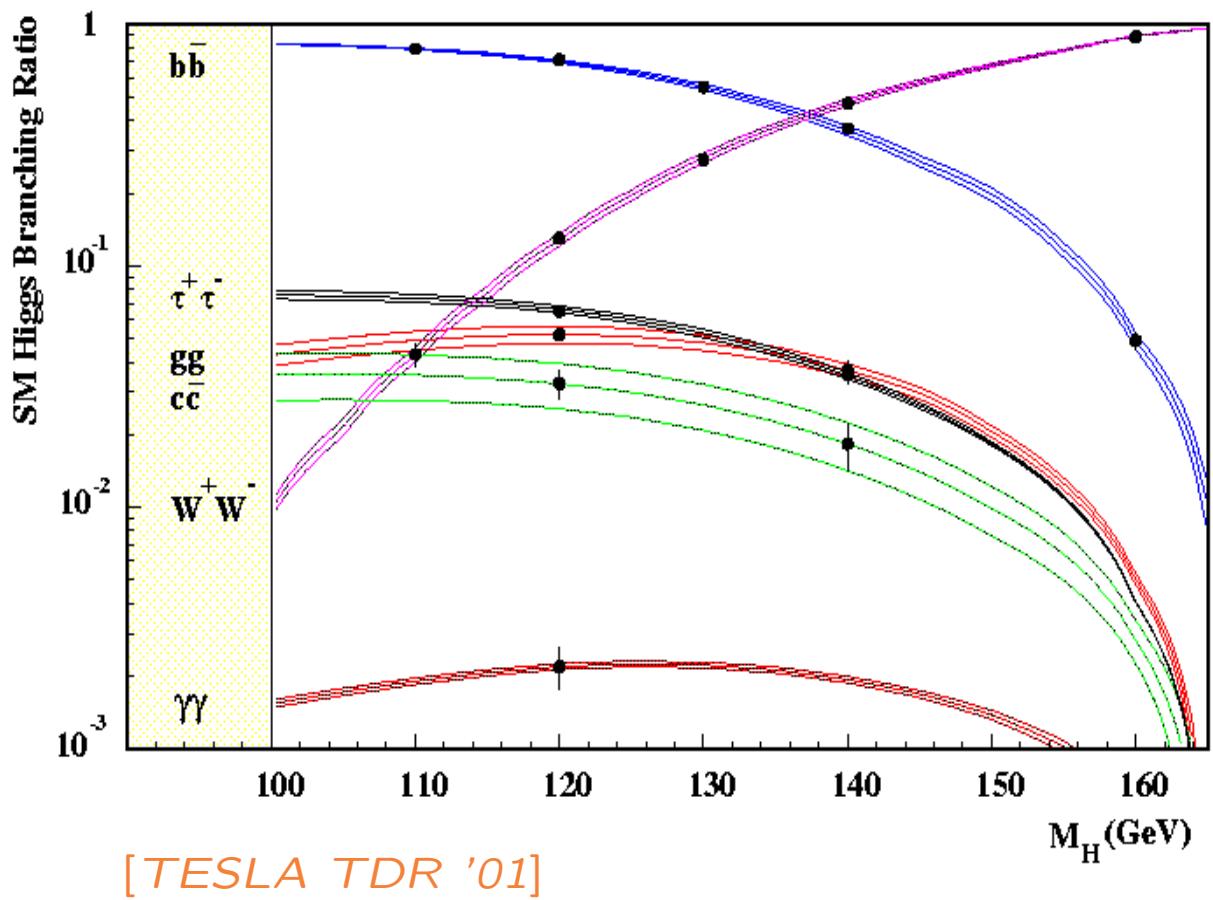


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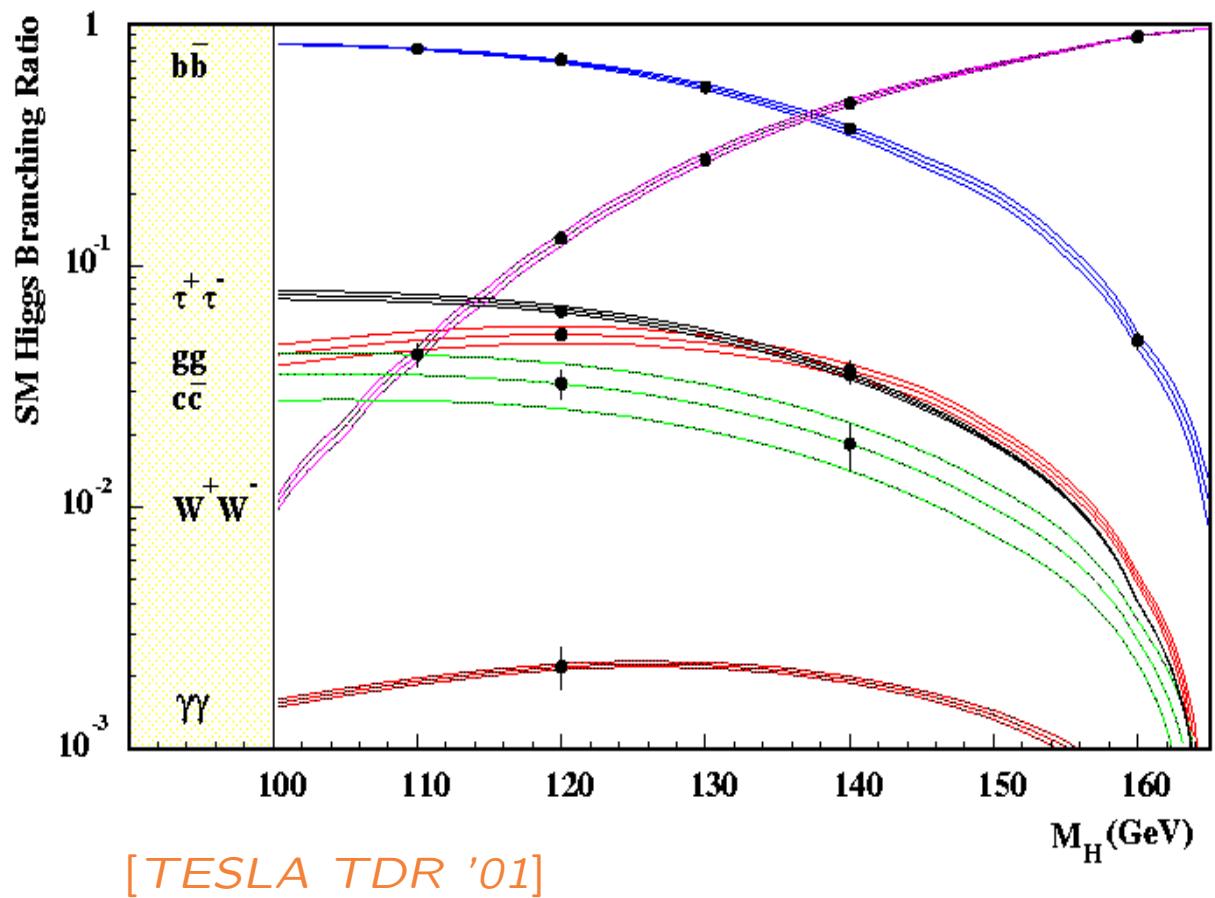
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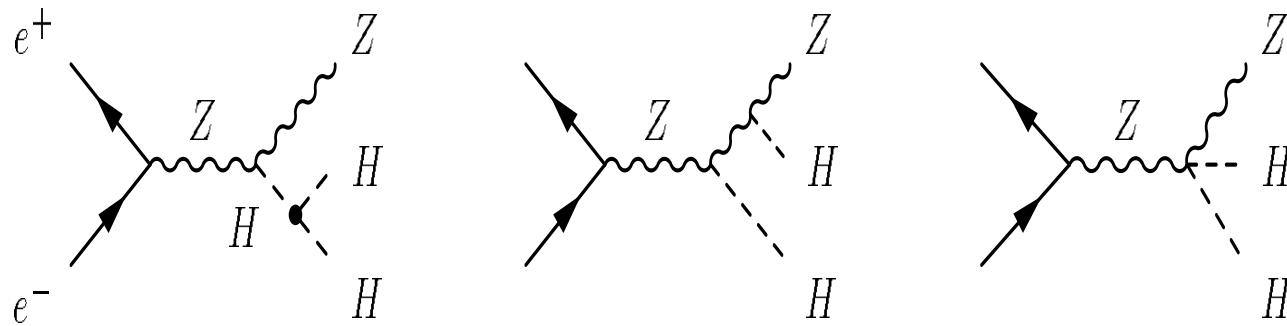


But do we need the ILC precision?

YES! To discriminate between the SM and extensions

Step 5: measurement of the Higgs boson self-coupling

⇒ only possible at the ILC

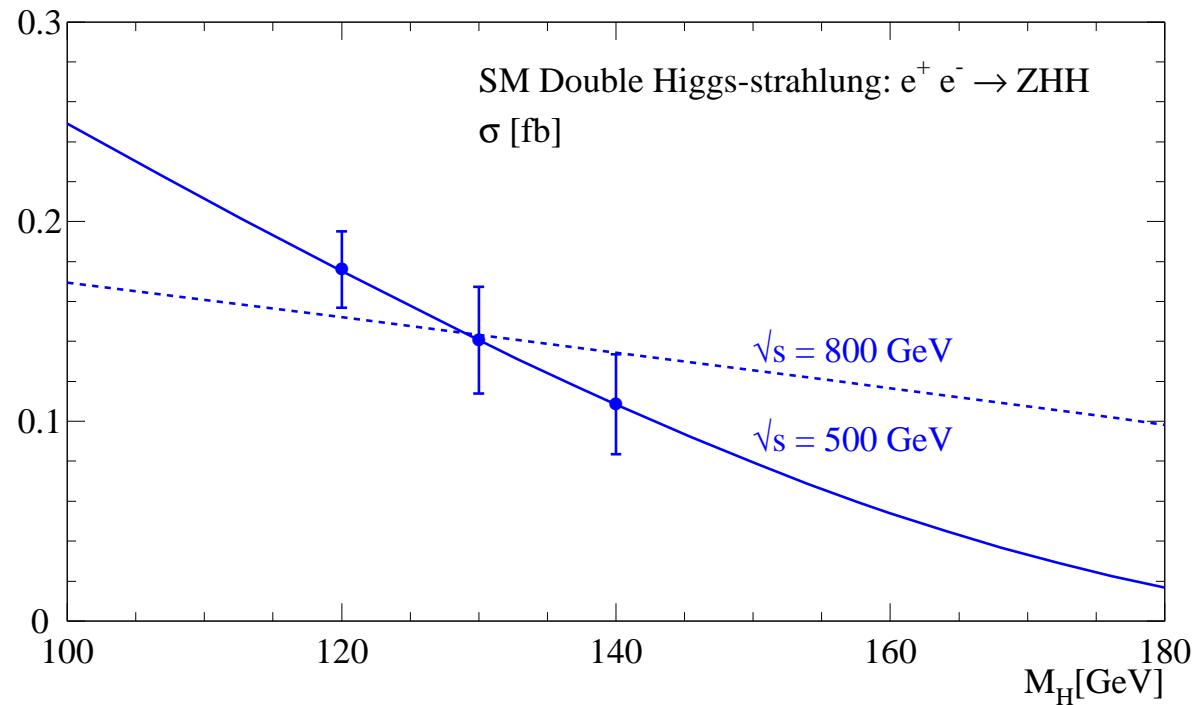


Parton-level study:

[Djouadi, Kilian, Mühlleitner,
Zerwas '99]

$1 \text{ ab}^{-1} \Rightarrow 20\text{--}30\%$

measurement of λ



Step 6: measurement of the Higgs boson self-coupling

⇒ easy at the ILC

Threshold scan for
 $\sigma(e^+e^- \rightarrow ZX)$:

$$X = H \Rightarrow \sigma \sim \beta$$

(for β see eq. (1))

20 fb^{-1}

⇒ identification easy

